# Index

Note to index: An n following a page number indicates a note on that page; an f following a page number indicates a figure on that page; a t following a page number indicates a table on that page.

## accuracy

factors affecting, 844t numerical solutions method, 843-845 aerodynamics, 120-121, 137-143. See also lift aeronautics, 5, 118 airfoil, 699f, 854, 857f angle of attack, 140-142f, 141f boundary layer thickness, 698-699 f lateral vs. upward flow, 638 f-641 uniform flow, 308–309, 308 f anisotropic bodies, and lift, 138 f, 141 anisotropic stress, 228, 297, 302, 304, 305, 310, 347, 347 f, 348. See also extra-stress tensor API (American Petroleum Institute) gravity, 881 Archimedes' principle, 259 Aristotle, 115 associative law for scalars, 58 with vectors, 59 asymptote, 178, 536 automobiles, and drag, 5, 117f average density, 52, 184 average fluid velocity, 9, 12, 13-14f average of function, calculating, 55-58, 184 ball valve. See valves and fittings basis vector Cartesian, 61f-63, 74-75, 615 curvilinear, 75-77, 76f orthonormal, 62-63, 64, 76, 78, 887 behavior of fluid, 838-874 compressible flow, 867-874 examples/solutions, 871-874 flows with curved streamlines, examples/solutions, 861-867 laminar flow, turbulent flow, 845-853 flow instability, 851-853 statistical modeling of turbulence, 846-851 lift, circulation, 853-861 numerical solutions method, 840-845 accuracy, 843-845 software packages, 842-843 strategy, 840-842 supersonic flow, 867-874

viscosity, drag, and boundary layers, 838-840 Bernoulli equation, 15-26, 578, 668-672, 706, 862 irrotational flow, 668-672 bicycle racing, 116f, 117-118 Bingham viscosity function, 109, 411t blood flow dynamics. See hemodynamics blunt objects, flow past, 705-718 body forces, 229*f*-230, 887 body moments, 298, 298n4 Bond number, 333 boundary conditions, 464-472 example/solution, 464-467, 470-472 falling film (incline) problem, 470-472, 471*f* finite velocity and stress, 469 flows in most common, 464-467, 465f no-slip at wall, 467 no-slip for rectangular duct, 550 Poiseuille flow in slit, 546 stress continuity, 468-469 surface tension, 469-470 symmetry, 467-468 velocity continuity, 469 boundary-layer analysis, 678 f boundary layers, 4-5, 7, 118-127 attached vs. detached, 5f, 710-714 blunt objects, 705-718 cylinders, 124-127f, 125f, 715f flat plate, 681-694 fluid behavior, 838-840 introduction to, 673-677 laminar, 120f, 121 examples/solutions, 678-696 inertia, 678 thickness, 692 f, 695-696 velocity profile, 697f and rotation, 689f separation of, 710f, 711f, 713f, 714-716 thickness of airfoil, 698-699f turbulent, 120f, 121 drag, 698 f examples/solutions, 696-705

918 Index

turbulent (cont.) thickness of, 698–699 f and viscosity, 678, 838-840 Brown, Robert, 362 Brownian motion, 319, 362-364 bulk deformation, 239, 881 buoyancy, 81-84, 257-259 and drag, 604–619, 605f, 608f, 609f, 611f, 612f, 618f neutrally buoyant particles, 177n4 buoyancy effect, 83, 305-306, 618f burst pipe problem, 601 f conclusion, 513-517, 515f flow-rate/pressure-drop relationship, 505-508 laminar flow, 495-497f, 496f calculus, 49-93 of continuous functions, 50-58 calibration, 881 Cannon-Fenske routine viscometer, 508f-511, 509*f* capacity, 8f, 881 capillary action, 147-148f, 328f-332 Cannon-Fenske routine viscometer, 508 f-511, 509f Carreau–Yasuda model, 409 f-411t, 410 f Cartesian coordinates, 61*f*-63, 74, 75*f*, 707*f*, 892-893 boundary conditions, 470-472, 471f continuity equation, 902t control volume, 200, 207-208, 214 equations incompressible fluids, constitutive equation, 904tincompressible fluids, motion, 902t, 903t incompressible fluids, power-law, 905t microscopic energy, 904t examples/solutions, 63-67 flow direction in ducts, 557 microscopic energy balance, 451-452 microscopic momentum balance, 460 right angle bend, 317-319, 389 stationary liquids, 256 tensors, 286, 288 Casson viscosity function, 411t Cauchy momentum equation, 411, 464, 846, 847, 848.849 microscopic balance, 440, 441-442, 448-450, 459, 460 cavitation, 815-816, 815f, 816f centrifugal pumps, 800-823, 801 f check valve. See valves and fittings choked flow, 867-868 f, 870 circulation, 853-861. See also lift examples/solutions, 858-861 Clay Mathematics Institute (CMI), 464n4 closed system, energy balance in, 751f-752Coanda effect, 139f, 140f coefficient of sliding friction, 171, 881-882

Colebrook correlation for pipe friction, 37, 536-538 commutative law for scalars, 58, 59 complex flows, 572-574, 718-733 dimensional analysis, 726-733 example/solution, 574-577 quasi-steady-state solutions, 577-580 unpredictability of, 718-720 unsteady-state solutions, 573-574 vorticity, 718-726 complex problems, 538f-540 method for solving, 538 compressible flow, 867-874 examples/solutions, 871-874 computational fluid dynamics (CFD), 839-840 conservative force, 882 conservation laws, 8-9 Bernoulli equation, 15-26 energy, 70, 87-88, 89f, 167 equations control volume balances, 444 findividual bodies, 444 f microscopic balances, 445 f mass, 70, 87-88, 89f, 167 momentum, 70, 87-88, 89f, 167 constant-head tank, 19f constitutive equations, 369-372, 882 example/solution, 373-393 generalized Newtonian fluid, 408-412f, 416, 460-461 incompressible fluids, 504, 904t inelastic (see inelastic constitutive equations) Newtonian fluids, 319-320, 369-375 power-law viscosity, 408-412 f, 441 stress, 4, 229, 349f, 390, 838-839, 850 stress tensor, 544 stress-velocity, 299, 319, 348 viscoelastic, 414-418, 415f, 441 contact forces, 228, 229 f, 230, 882 moving fluids, 283-320 free-surface stress effects, 320-322 isotropic and anisotropic stress, 302-320 total molecular stress, 284-302, 347 stationary fluids, 236-283 devices, 271-283 gases, 237*f*-241 liquids, 237f, 241-261 Pascal's principle, 263-270, 277-278 pressure on, 250f, 251-255, 261 principles of, 277 solids, 263-270 total stress tensor equation, 302 total molecular stress stress sign convention, 301-302 stress tensor, 294-297 continuity equation coordinate systems, 902t dimensionless, 520 microscopic mass balance, 429, 437-438, 447-448

919

# Index

pressure-driven flow, 549-550 continuum assumption, 155, 173-174 continuum model, 4, 175-187 continuum hypothesis, 181-184 field variables, 176-180 fluid particles, 184-187 control surface, 882 control volume (CV), 8, 9f, 174, 187-194, 766 conservation law equations, 444f definition, 190*f*, 882 examples/solutions, 194-201 forces on, 229-236 macroscopic, 212-217, 230f microscopic, 207-212, 230f microscopic parallelepiped CV, 311f momentum balance, 190-194 convective term, 189, 194-206, 435, 882. See also Reynolds transport theorem coordinate systems, 61-63. See also Cartesian coordinates; curvilinear coordinates; cylindrical coordinates; spherical coordinates differential operations, 898-905 Gibbs notation independence from, 438, 440 vector calculus, 61-67, 892-893 correlations, 11, 529-530, 882 example/solution, 531-540 coupling. See valves and fittings creeping flow, 119, 376f-377, 476f-477, 675f, 676. 677 f around sphere, 604-619, 605f, 608f, 611f, 612*f*, 623 dimensional analysis, 731 terminal speed, 619-621 Crocco's theorem, 667 cross product, 59, 60f, 63 cross-stream momentum balance, 864 cup-and-bob apparatus, 306f-308 curved streamlines, flows with, 149-153, 366-369, 373-375, 861-867 curvilinear coordinates, 74-84 cylindrical, 74-77, 75f, 76f examples/solutions, 78-84 spherical, 75f, 76f, 77 cylinders, flow around boundary layers, 124-127f, 125f pressure fields, 672-673 cylindrical coordinates differential operations in, 900t equations incompressible fluids, 504, 904t incompressible fluids, motion, 902t, 903t incompressible fluids, power-law, 905t microscopic energy, 904t flow-direction momentum balance, 557 d'Alembert, Jean le Rond, 662

Darcy-Weisbach equation, 36 data correlations. See correlations Dean vortices, 152 deformable media, motion of, 172-218 continuum model, 175-187 deformation rate, 156, 397, 403 DeKee viscosity function, 411t del operator, 71, 893-898 density field, 177-181 derivatives, 50-52, 182-183 examples/solutions, 52-54 diagonal stress tensor, 304, 347. See also isotropic stress differential operations, 70-71. See also partial differential equations examples/solutions, 71-74 in rectangular and curvilinear coordinates, 898-905 on vectors and tensors, 892-898 dimensional analysis, 7, 513, 726-733 creeping flow around sphere, 731 examples/solutions, 731-733 noncreeping flow, 628-638 example/solution, 638, 641-646 lift, 637-641, 638f terminal speed, 641-643 velocity/trajectory, 643-647, 644 f turbulent flow in pipes, 518-529 dipole-dipole forces, 229f, 231, 232t distributive law for scalars, 58 with vectors, 59 divergence, 432-433, 894 of tensor, 882, 896 of vector, 882, 895 divergence theorem, 432–433 dot product, 59, 60f, 62-63, 68-69 double integral, 58, 204 double-well manometer, 275-276f drag, 113-118 and automobiles, 117f and blunt objects, 716 and buoyancy, 604-619, 605f, 608f, 609f, 611*f*, 612*f*, 618*f* examples/solutions, 114, 117-118 fluid behavior, 838-840 form drag, 712-713 Newtonian fluid, 366f, 400-401, 484f-485 noncircular conduits, 563-564 nondimensional, 622, 623-624f, 640 potential flow, 660-661, 663-665 simple shear flow, 358-359, 366f steady drag flow, 400-401, 482-483 turbulent boundary layers, 698f viscous, 714, 716, 838-840 at wall (see wall drag) drag coefficient, 116 f-118, 622, 641, 882 correlations, 116*f*, 624, 625*f* ducts of constant cross section, 558 dyad/dyadic product, 67, 68, 889

d'Alembert's paradox, 662

friction factor

Darcy friction factor, 528n5. See also Fanning

920

## Index

dynamic pressure, 630 f-634, 652 and buoyancy effect, 649 definition, 630, 883 nondimensional, 639, 651, 663, 674 steady, two-dimensional, 683, 685 eddies, 845 f Einstein notation, 437, 883 electrostatic attraction, 230-231f, 244f elliptical cross section, laminar flow, 560-562, 561f, 562f Ellis viscosity function, 411t elongational flow, 378 f-379 empirical relation, 883 energy internal, 443 kinetic, 442 f, 443, 527 potential, 442 f - 443energy balance, 750-766 closed systems, 751-752 mechanical energy balance, 8-49, 759-766 open systems, 753-759 energy conservation, 70, 87-88, 89 f, 167, 442-445 energy velocity-profile parameter, 763, 766t, 768 entanglement forces, 232f, 232t equilateral triangle cross section, 559f-560equivalent pressure. See dynamic pressure Ergun correlation, 567, 569 error, roundoff, 27, 41, 46, 843, 845, 888 Eulerian description of fluid mechanics, 190-206, 883-884 Euler's method, 646 external flows, 4, 600-733 definition, 884 dimensional analysis, 726-733 examples/solutions, 731-733 vorticity, 718-726 examples/solutions, 724-726 extra-stress tensor, 304, 364-365, 378, 884 falling film (incline) problem, 174–175 f boundary conditions, 470-472, 471f conclusion of, 379-386f flow rate/average velocity, 12, 390-392 microscopic balances, 452-457 microscopic control-volume, 207-212, 208f, 209f, 211f Newtonian fluids, 364–365 f stress-tensor components, 310-316, 311f, 312f, 314t total force on wall, 473-475 Fanning friction factor (f), 35–37, 39, 513, 528 ducts, 570 flow-rate/pressure-drop, 532 smooth/rough commercial pipes, 537 f Faraday's law of induction, 153 ferrifluids, 298n4 field variables, 176-177 example/solution, 177-180f, 178f, 179f

first law of thermodynamics, 443 flat plate, flow past, 681-705 flow cytometry, 7fflow-direction component of fluid velocity, 682f, 691*f* flow instability, 851-853 flow rate, 194-201, 390-392, 481-483 flow-rate-measurement devices. examples/solutions, 772-779 flow variables, examples/solutions, 13-15 flow-visualization videos, 106 fluctuation-averaged equations of change for turbulent flow, 848-849 fluid acceleration, 862 f fluid-centered view, 113 fluid contact forces, 203 fluid-force equation for ideal gases, 245 sphere in creeping flow, 614, 617 sphere in noncreeping flow, 626 sphere in uniform flow, 626 fluid-layer separation, 714 fluid particles, 184–187 f, 185 f fluid(s) definition, 233, 884 properties of, 283 fluid-stress modeling, 4 flux/temperature law, 299 form drag, 712-713 free-stream velocity, 674f free-surface effects, 145-146, 884 free-surface stress effects, 320-322 capillary action, 328-332 examples/solutions, 322-332 spherical water droplet in air, 322-328, 323ffriction, 792f examples/solutions, 34-49 Fanning friction factor (f), 35-37, 39 no friction, no work, examples/solutions, 15-26 friction factor. See also Fanning friction factor; Darcy friction factor circular ducts, 555 correlations, 35, 37, 529–540, 532 f laminar slit flow, 555 noncircular conduit, 555 packed bed, 567 Reynolds number, 36, 530–533, 531f friction loss, 807 f. See also head loss friction-loss factors for fittings laminar flow 43t turbulent flow, 43t Froude number, 523, 529, 530, 633, 830 fully developed flow, 884 function average of, 55-58 maximum value of, 52-54 Galilei, Galileo, 115 gases, static, 237 f - 241examples/solutions, 240-241

921

# Index

ideal gas law, 237-238 kinetic-molecular theory of, 238t-240 gate valve. See valves and fittings gauge pressure, 112, 266, 268, 770f, 772, 884 Gauss-Ostrogradskii divergence theorem, 432-433. See also Stokes's theorem Gauss's integral theorem, 884-885 g<sub>c</sub>, 29n2, 47, 885 generalized Newtonian fluid (GNF) constitutive equation, 408-412 f, 416, 460-461 geological flows, 154 geometrically complex flows, 580-581 example/solution, 581-585 Gibbs notation, 71, 85, 89, 898 boundary conditions, 468 continuity equation, 447, 605, 680 definition, 885 flow-direction momentum balance, 557 independence from coordinate systems, 438, 440 molecular contact forces, 299 nondimensionality, 523, 632, 731, 732 stress tensor, 285, 288, 293, 303, 346 globe valve. See valves and fittings golf balls, 119*f*-120*f*, 121*f* gradient function, 179, 180f, 894, 895. See also del operator gravity field equation, 208 gravity forces, ratios, 333, 523, 830 Hagen-Poiseuille equation flow-rate/pressure-drop, 111 f, 507, 511, 532 flow through capillary, 509 laminar flow, 128, 497 steps to, 511 Hamel flow, 581f, 582f-583 head, 8f, 47-48, 769, 777, 885 head loss, 36, 41, 818-819, 821, 885. See also friction loss heart-lung machine (HLM), 151-152f hemodynamics, 5, 6f, 129-130t, 130f hotel tower example and boundary layers, 124-127f, 125f pressure fields, 672-673 hydraulic diameter, 557 and Poiseuille equation, 554-558 hydraulic jump, 826-830, 827f hydraulic lifts, 144f, 277-282 examples/solutions, 278-282 hydraulic radius, 557n11 hydroelectric power, 30-34, 31f hydrogen bond, 229f, 230, 231f, 232t hydrostatics, 236-283. See also contact forces, stationary fluids ideal gas law, 237-238, 239, 240, 244, 245, 260, 871-872 incline problem. See falling film (incline) problem

incline problem. *See* falling film (incline) problem indeterminate vector product, 67–68, 70, 290, 292, 885, 889, 895. *See also* tensor induction, 30f, 153-154 inelastic constitutive equations, 402-414, 441 example/solution, 403-404, 403-414, 406, 407-408 generalized, 408-414, 412f planar-jet flow, 403 f-404, 407-408 power-law viscosity function, 408-409, 411t, 412-414 rate of deformation, 403, 406 inertial forces circular flow, 150 laminar boundary layers, 678 sudden acceleration of wall, 575-577 viscous forces vs., 676 inertia vs. viscosity, 676 inner product, 59 integral, 54-55, 182-183 example/solution, 55-58 over arbitrary limits, 436, 437 f interfacial forces, 148-149 intermolecular forces, 230–232t, 231f potential energy function, 242 f, 243-244 intermolecular repulsion, 242, 243, 244 f, 263, 320 internal energy, 443 internal flow, 4, 494, 885-886. See also laminar flow; turbulent flow entry flow, 127, 583-584 noncircular conduits, 540-564, 570-572 packed bed, 564-569 pipe flow, laminar, 497 pipe flow, turbulent, 511 inviscid fluid, 651, 675 f, 886. See also potential flow ion-dipole forces, 229f, 231, 232t irrotational flow, 668-672, 855, 857n1, 886. See also vorticity irrotational regions, 720, 721f isotropic pressure distribution, 156, 250 f isotropic stress, 228, 302-320 examples/solutions, 303-319, 347, 886 moving fluid, 347 f, 348 stationary fluid, 323 iterative solution, 514-515f, 539f Kelvin's circulation theorem, 864, 865-866 kinematics, 886 kinematic viscosity. See viscosity, kinematic kinetic energy, 442f, 443, 527 kinetic-molecular theory of gases, 238t-240, 241-242 Korotkov sound, 129 Kronecker delta, 886 Kutta-Joukowski theorem, 856-857, 858, 861 Lagrangian description of fluid mechanics, 87. See

*also* Eulerian description of nata meenanics, 677 Sec also Eulerian description laminar boundary layers, 120 *f* , 121, 678 examples/solutions, 678–696 inertia in, 678

922

# Index

laminar boundary layers (cont.) thickness of, 692f, 695-696 velocity profile, 697 f laminar flow, 4, 5f, 11, 127-137, 845-853. See also turbulent flow; internal flow burst pipe problem, 495–497f, 496f, 505–508 Cannon-Fenske routine viscometer, 508 f - 511, 509 f conduit with equilateral triangular cross section, 559 f-560 defining, 128f, 512f elliptical cross section, 560-562, 561 f, 562 f example/solution, 497-511 examples/solutions, 131-137, 135f flow instability, 851-853 flow-rate/pressure-drop relationship, 497–505f, 502f - 503ffriction factor in slit flow, 555 friction-loss factors, 43t Hagen-Poiseuille equation, 128, 497 microscopic balances equation, 497-505f, 502*f*-503*f* noncircular conduits, 540-544 Poiseuille number and hydraulic diameter, 554-558 average velocity in triangular duct, 562-563 drag in laminar flow, 563-564 ducts of constant cross section, 558 elliptical cross section, 560-562, 561f, 562 f equilateral triangle cross section, 559f-560example/solution, 558-569 pressure-driven flow through packed bed, 564-569, 565 f Poisson equation, 541-544 problem solving strategy, 513f turbulent flow vs., 127-137, 762f Laplacian, 894-895 of scalar, 896 of vector, 896-897 Leibniz rule (constant volume), 435, 438 lift, 137-143, 853-861 angle of attack and, 138f, 139-140 anisotropic bodies, 138f, 141 calculating, 142-143 examples/solutions, 858-861 lateral vs. upward flow, 638 f-641 lift coefficient, 140-141f, 142f liquids, stationary, 237f, 241-261. See hydrostatics confined, 263 examples/solutions, 251-260 momentum balances, 245-251 pressure on, 250f, 251-255, 261-262 unconfined, 263f London dispersion forces, 229f, 231f, 232t Lorentz force, 154 lubricants, 107, 472, 473 f lubrication approximation, 585 Mach number (Ma), 145

macroscopic balance equations, 9, 741-830 derivation of, 741-766 energy balances, 750-766 mass-balance equation, 742-745 momentum-balance equation, 745-750 use of. 766-830 flow-rate-measurement devices, examples/solutions, 772-779 open-channel flow, examples/solutions, 823-830 pressure-measurement devices, examples/solutions, 769-772 pumps, examples/solutions, 800-823 valves and fittings, examples/solutions, 779-800 macroscopic Bernoulli equation, 15-26 macroscopic closed-system energy balance, 751-752 macroscopic control-volume, 212-217, 230f example/solution, 212-217 macroscopic energy balance, 750-766, 768 macroscopic mass balance, 742-745, 766-767 macroscopic momentum balance, 767-768, 779 f equation, 745-750 macroscopic open-system energy balance, 751, 753-759 magnetohydrodynamics (MHD), 5, 153-154f, 155 f magnitude of tensor, 405 manometers, 271-277, 274f, 272f definition, 886 examples/solutions, 274-276 manometer tubes, 770, 770f, 774-776, 774f Marangoni effect, 148, 149 f, 333 mass balance, 433-438. See macroscopic mass balance; continuity equation; mass conservation continuity equation, 429, 437-438 example/solution, 436-437 f mass-body-motion approach, 174 mass conservation, 70, 87-88, 89f, 167, 433-438 continuity equation, constant density, 572 mass flow rate, 12, 14, 195, 197 pentahedron example, 198-201 matrix algebra, 69 maximum value of function, calculating, 52-54 mechanical energy balance (MEB), 8-49, 759-766 application method, 13t definition of terms, 10 derivation, 759-766 flow variables, examples/solutions, 13-15 with friction, examples/solutions, 34-49 macroscopic energy balance and, 750 with no friction, no work, examples/solutions, 15 - 26pumps and, 805 f requirements for using, 11t with shaft work, examples/solutions, 26-34 volumetric flow rate-average velocity relationship, 12, 13 memory fluid, 109, 416 meniscus effect, 146f

macroscopic analysis, disadvantages of, 9

923

## Index

microfluidics, 5-6, 7f, 541 microscopic balance equation, 71, 429 Cauchy momentum, 440, 441-442, 448-450, 459, 460 continuity equation, 447-448 deriving equations, 430-432 energy balance, 442-445 falling film (incline) problem, 452-457 flow-direction momentum balance for Poiseuille flow in conduit, 549–554, 550 f, 551 f mass balance, 433-438 continuity equation, 429, 437-438 example/solution, 436-437f momentum balance, 438-442, 440, 448-450, 459-463, 460 Navier-Stokes, 441, 449, 450-451f, 454-456, 457-458, 463-464, 499 Newtonian fluids, 457-459 non-Newtonian fluids, 459-463 problem-solving procedure, 446-447, 452f, 498*f* steady flow for laminar pipe flow, 497-505f, 502 f - 503 fvelocity and stress field quantities, 472-473 creeping flow, 476 f-477 example/solution, 473-478 falling-film (incline) problem, 472-475 flow rate and average velocity, 481-483 torsional rheometer, 478-481, 479f total force on wall, 472-473 velocity and stress extrema, 483-485 microscopic control-volume, 230f example/solution, 207-212 microscopic parallelepiped, 311f molecular forces definition, 886 dipole-dipole, 229f, 231, 232t electrostatic attraction, 230-231f, 244f hydrogen bond, 229 f, 230, 231 f, 232t intermolecular repulsion, 242, 243, 244f, 263, 320 ion-dipole, 229f, 231, 232t London dispersion, 229 f, 231 f, 232t polymer entanglement, 229f, 231, 232f, 232t, 396 momentum balance, 147, 167-171, 438-442. See also microscopic balance equation general fluids, 438-440 Newtonian fluids, 441-442 on skydiver at terminal speed, 603 momentum conservation, 70, 87-88, 89f, 167, 184-186, 245 momentum flow rate, 195-196, 198, 201-206 momentum velocity-profile parameter, 746, 747-749, 766f, 767 Moody Plot, 38f, 568f, 570 motor oil, viscosity of, 107 National Committee for Fluid Mechanics Films (NCFMF), 333, 852-853

in coordinate systems, 429-430, 903t dynamic pressure term, 631, 652 flow around sphere, 606-610 flow rate/pressure-drop relationship, 498-500 geometrically complex flows, 580-585 microscopic momentum balance, 441, 449, 450-451 f, 454-456, 457-458, 463-464, 499 momentum conservation, 542-543 nondimensional, 421, 519-523, 528, 535, 631-632, 674-675 pressure-driven flow in duct, 550 regular pressure term, 631 semi-infinite fluid bound by wall, 575 net positive suction head (NPSH), 814-823, 818f examples/solutions, 817-823 neutrally buoyant particles, 177n4 Newton, Sir Isaac, 316, 361, 886 Newtonian fluids, 364-393. See also non-Newtonian fluids constitutive equation, 319-320, 369-373 creeping flow around solid sphere, 376 f - 377drag flow, 366f, 484f-485 elongational flow, 378 f-379 equations for all incompressible flow problems, 572 falling film (incline) problem, 364–365f, 379-386f, 390-392 flow around sphere, 366*f*, 368–369*f*, 374-375 microscopic balance equation, 457-459 molecular fluid force, 301-302 momentum balance, 441-442 planar-jet flow, 366f-368f, 373-374 right angle bend problem, 386–390, 387f, 392-393 shear flow, 364-365f steady-drag flow, 400-401 Newton's law of viscosity, 108-109, 360-361 example/solution, 157-158 Newton's second law of motion, 167-168f, 185 control volume (see Reynolds transport theorem) definition, 886-887 examples/solutions, 168-172 terminal speed, 602, 619, 642 noncontact forces. See body forces noncreeping flow, 628-638 around sphere, 622-623, 728-729, 729 f drag coefficient, 623-625, 624, 625f, 641 terminal speed, 625-628 example/solution, 638, 641-646 fluid-force equation, 626 lift, 637-641, 638f terminal speed, 641-643 velocity/trajectory, 643-647, 644f nondimensional flow equations drag, 622, 623-624f, 640 dynamic pressure, 639, 651, 663, 674 Navier-Stokes equation, 421, 519-523, 528, 535, 631-632, 674-675

Navier-Stokes equation, 121, 572, 723, 731, 839–840

924

### Index

nondimensional flow equations (cont.) Reynolds number, 523, 622, 623-625f, 624f wall drag, 527-528 nondimensional pressure distributions, 675 f nonlinear constitutive models, 417 non-Newtonian fluids, 5, 393-418. See also Newtonian fluids inelastic constitutive equations, 402-403 example/solution, 403-404, 406, 407-408, 412-414 generalized, 408-414, 412f planar-jet flow, 403 f-404, 407-408 power-law viscosity function, 408-409, 411t, 412-414 rate of deformation, 406 microscopic balance equation, 459-463 shear-induced normal stresses, 397, 399-402, 399f, 400f viscoelastic constitutive equations, 414-418, 415*f* viscosity, 394-397 non-Newtonian 394-397 shear-thickening, 394–397, 395 f, 398 f shear-thinning, 396f-397, 398f, 412-414 normal forces, 233 f-234, 284 normal stresses, 397, 399-402 numerical solutions method, 840-845, 841 f, 842 f accuracy, 843-845 software packages, 842-843 strategy, 840-842 open-channel flow, 853f examples/solutions, 823-830, 824f gravity in, 823 open system, energy balance in, 751f, 753-759 ordinary differential equations (ODEs), examples/solutions, 91-93 orifice plate (orifice meter), 34, 811, 887 orthonormal basis vectors, 64, 76, 78, 887 outer flow potential-flow solution, 121, 123, 126 pressure distribution, 684-685, 686, 698, 700, 708-710f, 715 streamlines, 122f, 123 outer product, 59

pail-and-scale method, 16fparallel-plate apparatus boundary conditions, 464-467, 465fderivatives, 52-54, 53fforce-velocity relationship, 360Newtonian fluid drag flow, 484f-485Newtonian fluids, 457-459non-Newtonian fluids, 459-463Poisson equation for velocity and stress fields, 544-549, 545f, 546f, 547f, 548fshear-induced normal stresses, 399-400simple shear flow, 349-350f, 355-358, 357f

steady drag flow, 482-483 torsional rheometer, 478-479f velocity field, 351 viscosity, 364, 394 partial derivatives, 54 partial differential equations (PDEs), 6, 8, 9f, 91 definition. 887 examples/solutions, 91-93 particulate flow, 154-157, 156f Pascal's principle, 263-271, 887-888 pathlines of the flow, 86f-87perfect fluid, 651 pipe flow. See internal flow dimensional analysis of, 135 Pitot tube, 771-772, 771f, 774-776, 774f, 777 f planar-jet flow Newtonian fluids, 366*f*-368*f*, 373-374 non-Newtonian fluids, 403 f-404, 407-408 Poiseuille, Jean Marie, 361 Poiseuille equation burst pipe problem, 495-497 f, 496 f drag at wall, 524-529, 544-549 duct of elliptical cross section, 560-562, 561 f, 562 f examples/solutions, 92-93 and hydraulic diameter, 554-569 momentum balance, 543-544 rectangular duct, 549–554, 550 f, 551 f velocity and stress fields in slit, 544–549, 545 f, 546f, 547f, 548f Poiseuille number (Po), 557, 560, 561f, 562f, 570 Poisson equation, 554-555 polymer entanglement, 229*f*, 231, 232*f*, 232*t*, 396 potential energy, 442f-443 potential energy function, 242fpotential flow, 121-122, 650-673, 675, 677 f drag on sphere, high-Reynolds-number, 660-661 examples/solutions, 651-657, 660-661, 663-665, 666-673 flow around sphere, high Reynolds number, 651-657f, 658f flow around sphere, no drag, 676-677f irrotational flow around cylinder, 670-672 pressure distribution, irrotational flow, 668-670 pressure distribution, steady, incompressible, potential flow, 666-668 pressure distribution of flows, 672-673 pressure distribution on drag, 663-665 rules for using solutions, 670 power-law viscosity function, 408-409, 409f, 411t, 412-414 Prandtl, Ludwig, 118, 678-679, 714, 851 Prandtl correlation burst pipe problem, 513–517, 515f

Index

925

modified, for turbulent flow in noncircular ducts, 570 turbulent pipe flow, smooth pipe, 512, 533, 537-538 pressure, equivalent. See dynamic pressure pressure drag, 714, 716 pressure-measurement devices, examples/solutions, 769-772 pressure-relief valves, 868f pressure waves, 869, 869 f, 871 f pumping-head curves, 801-804, 806, 807f, 809f pumps, 6, 8f, 800-823 net positive suction head, examples/solutions, 814-823 size of, examples/solutions, 801-814 quasi-steady-state solution, 573, 577f-579, 588f rate-of-deformation tensor, 405. See also deformation rate rectangular coordinate system. See also Cartesian coordinates differential operations in, 899t rectangular duct, 549-554, 550f, 551f laminar flow, elliptical cross section, 560-562, 561f, 562f repulsion, intermolecular, 242, 243, 244 f, 263, 320 return bend. See valves and fittings Reynolds, Osborne, 128-129, 888 Reynolds number, 18, 28-29, 128-132, 513, 727 circular ducts, 555, 556-558 examples/solutions, 131-137 flow patterns, high Reynolds number, 647-650, 648f, 649ffriction factor, 530–534, 531f, 532f, 555, 556-558 Hamel flow, 582f-583 high, drag on sphere, 660-661 high, flow around sphere, 651-657f, 658f laminar flow, equilateral triangular cross section, 559*f*-560 lift coefficient as function of, 140-141f, 142f noncircular duct, 570 nondimensional flow, 523, 622, 623-625f, 624 fpacked bed, 567-568f smooth/rough commercial pipes, 537f Reynolds transport theorem control volume, 187-189, 205-206, 228, 346 definition, 888 macroscopic control volume, 213-214 momentum balance, 438, 439, 451 moving fluids, 283-284 right angle bend problem, 387 simple shear flow, 355 stationary fluids, 245 rheology, 5, 109. See also non-Newtonian fluids right angle bend problem, 430, 779-781 conclusion of, 386–390, 387f

macroscopic control volume, 212-217, 213 f, 214fmolecular stresses, 316-320, 317f relative magnitudes of terms, 392-393 right-hand rule, 60f rigid bodies, motion of, 167–168, 173 f examples/solutions, 168-172 rod-climbing, 400 f, 410 rotameter, 888 rotation, and boundary layers, 689 f rotational flow, 720, 721f roughness of manufactured pipes, 535-536t roundoff error, 27, 41, 46, 843, 844, 888 scalars associative law for, 58, 59 commutative law for, 58, 59 definition, 888 distributive law for, 58, 59 product, 59 Schedule 40 piping, 13 Scott, David (astronaut), 116f secondary flow, 149-153, 151 f separation, of boundary layers, 710f, 711f, 713f, 714-716 shaft work, 10, 11, 26-34 examples/solutions, 26-34 shear flow, simple, 348-364 shear force, 233f-234f, 888 shear-induced normal stresses, 397-402 shear stress, 351-359 shear thickening, 394-397, 395 f, 411t shear thinning, 396f-397, 398f, 411t, 412-414 shock wave, 873 f simple shear flow, 348-359 drag flow, 358-359 examples/solutions, 355-358, 359 stress field, 351-355 velocity field, 350-351f, 352f viscosity, 360-361 molecular interpretation of, 362-364 siphon, 21-25 skydiving, 601-604, 619-621, 625-628 sliding-block with friction, 170-172 without friction, 168-170, 168f, 170f slope of secant line, 51f of tangent line, 50-52, 51f software packages, for numerical solutions method, 842-843 solids, and transmission of forces, 263-270 sound, speed of, 869-870 spatial derivatives, 70-71, 892-893 specific gravity (SG), 797, 798, 889 sphere dimensional analysis, 628-641 examples, 641-646 flow, creeping. See creeping flow flow, noncreeping, 622-627

926

#### Index

sphere (cont.) flow patterns, 647 pressure, creeping, 610 pressure, potential, 656, 666-668 potential flow, 650-665 spherical coordinates, 708f differential operations, 901t equations incompressible fluids, constitutive equation, 904*t* incompressible fluids, motion, 902t, 903t incompressible fluids, power-law, 905t microscopic energy, 904t stagnation point, 675, 889 statistical models of turbulence, 846-851 Stokes's flow. See also creeping flow estimate of terminal speed, 621 Stokes-Einstein-Sutherland equation, 619 Stokes's theorem, 889 stream function, 122–123, 714–715f, 775f curved streamlines, examples/solutions, 861-867 flows around sphere, 610-611f, 612fflows with curved, 149-153, 150 f streamlines. See stream function stress constitutive equation, 4, 229, 349f, 390, 838-839, 850 stress sign convention, total molecular stress, 298-301 example/solution, 301-302 stress tensor, 284-305 extra-stress tensor, 304, 364-365, 378, 884 matrix form, 310f stationary fluids, 347 symmetry of, 405 total molecular stress, 286-293, 347 examples/solutions, 294-297 substantial derivative, 84-90 examples/solutions, 89-90 physical meaning of, 84-88 supersonic flow, 143-145, 867-874 surface integral, 202 f surface tension, 145-149, 146f, 147f, 320-333 capillary effect, 328-332 dimensionless numbers, 333 droplet, 322-328 nonspherical surface, 326-328 representative values, 321t tensor. See also stress tensor; indeterminate vector product definition, 67-69, 889-890 divergence of, 882, 896

dot product of, 68–69 examples/solutions, 69–70 magnitude of tensor, 405 rate-of-deformation tensor, 405 symmetric tensor, 405 vector calculus, 67–70 terminal speed, 602, 603, 619-621, 625-628, 641-643 test section, of flow of interest, 843 f torque, 65, 66*f*-67, 478-481, 479*f* Torricelli's law, 20 torsional rheometer, 478-481, 479 f total molecular stress, 284-302 stress sign convention, 298-301 example/solution, 301-302 stress tensor, 286-293, 347 examples/solutions, 294-297 trim of a valve. See valve trim triple integrals, 58, 431 tube flow. See internal flow turbine, 30-33 turbulent boundary layers, 120f, 121 drag, 698 f examples/solutions, 696-705 thickness of, 698-699f turbulent flow, 4, 5f, 11, 127-137, 511-513, 728-729f, 845f-853. See also laminar flow burst pipe problem, 513-517, 515 fdata correlations, 529-540 defining, 128f, 512f dimensional analysis, 518-529, 534-535 examples/solutions, 131-137, 135f, 513-517, 524-525, 531-533, 534-535, 538-540 flow instability, 851-853 flow splits, 538f - 540friction-loss factors for, 43t laminar flow vs., 127-137, 762 f momentum balance, 517-518 noncircular conduits, 570-572 Prandtl correlation for noncircular ducts, 570 problem solving strategy, 513f smooth pipe, Prandtl correlation, 512, 533, 537-538 statistical modeling of turbulence, 846-851 wall drag, 527-528, 536f union. See valves and fittings unit vector, 59, 60, 890. See also basis vector unsteady, incompressible, unidirectional flow, 573-574 valves and fittings ball valve, 42 f check valve, 42f

coupling, 44t defining, 890–891 examples/solutions, 779–800 friction-loss factors, 43t gate valve, 42f globe valve, 42f return bend, 42f union, 42f valve trim, 890 vapor lock, 24, 891 vector calculus, 58–84, 892–898

927

# Index

coordinate systems, 61-67, 892-893 curvilinear coordinates, 74-84 differential operations, 70-74 tensors, 67-70 vorticity, 7, 152-153, 718 vectors algebra laws for, 59 cross product of, 59, 60f, 63definition, 891 direction of, 59, 61 dot product of, 59, 60f, 62-63 magnitude of, 59, 60-61 orthonormal, 62-63 velocity direction and magnitude of, 744fin turbulent vs. laminar flow, 762f velocity field, 176-177, 891 velocity profile calculating flow rate from average velocity, 481-483 converging flows, 583 f - 584 fenergy velocity-profile parameter, 763, 766t, 768 equilateral triangle, 559-560 flow around sphere, 709 f flow down incline, 379-385, 386f laminar boundary layers, 697 f laminar flow in pipes, 502flaminar flow past flat plate, 691, 695-696 momentum velocity-profile parameter, 746, 747-749, 766 f, 767 potential flow and creeping flow, 660 potential flow around sphere, 709f quasi-steady-state solution, 578 rectangular duct, 554-555, 557 semi-infinite fluid wall suddenly set in motion, 575 simple shear flow, 349, 350-351f steady drag, 352f steady flow in narrow slit, 55-58, 56f turbulent boundary layer, 696, 697 turbulent pipe flow, 749 two-dimensional, 543, 550 Venturi meter, 15, 16-19, 772-773, 773 f viscoelastic constitutive equations, 414-418, 415*f*, 441 viscosity, 106-113, 114t, 115t, 360-361, 361t. See also drag Bingham function, 109, 411t boundary layers, 838-840

Casson function, 411t DeKee function, 411t drag, 714, 716, 838-840 effect on pressure, 677f Ellis function, 411t examples/solutions, 110-113 familiar materials, 114t familiar materials, compared on logarithmic scale, 115*f* fluid behavior, 838-840 kinematic, 38, 107, 891 laminar boundary layers, 678 measuring using Cannon-Fenske viscometer, 508*f*-511, 509*f* molecular interpretation, 362-364 motor oil, 107 Newton's law, 108-109, 157-158, 360-361 non-Newtonian fluids, 394-397, 412-414 parallel-plate apparatus, 364, 394 power-law function, 408-409, 411t, 412-414 simple shear flow, 360-364 volumetric flow rate, 9, 12, 194-195, 197 volumetric flow rate-average velocity relationship, 12, 13 vortex tube, 865–866, 865 f vorticity, 7, 152-153, 718-726, 721f, 722f, 723f, 891 examples/solutions, 724-726 vorticity-transport equation, 725-726 wake region, 120 wall drag noncircular conduits, 555 nondimensional, 527-528 Poiseuille flow, 524-529, 544-549 turbulent flow in circular pipe, 527-528, 536f water striders, 147, 148f Weber number, 333 weir, 891 Weissenberg effect, 400 f wicking, 148 work, 442, 750 energy and, 442-443 flow work, 756 f yield-stress fluid, 109 f. See Bingham viscosity function

Young–Laplace equation, 328. See also surface tension