PROBLEMS FOR CHAPTER 1

1-1

A sphere 1.4 cm in diameter is placed in a freestream of 18 m/s at 20°C and 1 atm. Compute the diameter Reynolds number of the sphere if the fluid is (a) air, (b) water and (c) hydrogen.

1-2

A telephone wire 8 mm in diameter is subjected to a crossflow wind and begins to shed vortices. From figure, what wind velocity in m/s will cause the wire to "sing" at middle C (or 256 Hz)?

1-3

If the wire in Problem 1-2 is subjected to a crossflow wind of 12 m/s, use Figure 1-9 to estimate its drag force (in N/m)

1-4

For oil flow in a pipe far downstream of the entrance (Figure 1-10 and 1-11), the axial velocity profile is a function of r only and is given by:

$$u = \left(\frac{C}{\mu}\right)(R^2 - r^2)$$

where C is a constant and R is the pipe radius. Suppose the pipe 1 cm in diameter and u_{max} is 30 m/s. Compute the wall shear stress in Pa if μ=0.3 kg/m.s.

1-5

A tornado may be simulated as two-part circulating flow in cylindrical coordinates, with:

$$v_r = v_z = 0$$

$$v_\theta = r\omega \qquad if \quad r \le R$$

$$v_\theta = \frac{\omega R^2}{r} \qquad if \quad r > R$$

Determine:
(a) the vorticity and
(b) the strain rates in each part of the flow.

1-7

A two-dimensional unsteady flow has the velocity components:

$$u = \frac{x}{1+t} \qquad v = \frac{y}{1+2t}$$

Find the equation of the streamlines of this flow which pass through the point (x_0, y_0) at time $t = 0$.

1-8

Using Eq.(1-2) for inviscid flow past a cylinder, consider the flow along the streamline approaching the forward stagnation point $(r, \theta) = (R, \pi)$. Compute (a) the distribution of strain rates ϵ_{rr} and $\epsilon_{r\theta}$ along this streamline and (b) the time required for a particle to move from the point $(2R, \pi)$ to the stagnation point.

1-9

A commonly used equation of state for water is approximately independent of temperature:

$$\frac{p}{p_0} \approx (A+1)\left(\frac{\rho}{\rho_0}\right)^n - A$$

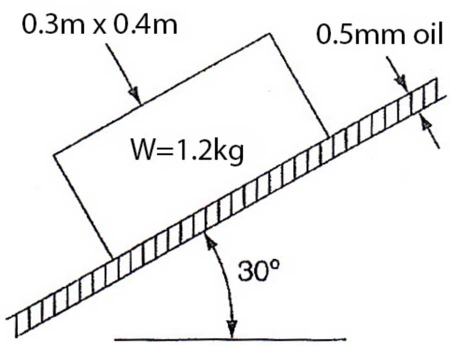
where $A \approx 3000$, $n \approx 7$, $p_0 \approx 1\, atm$, $\rho_0 \approx 998\, kg/m^3$. From this formula, compute (a) the pressure (in atm) required to double the density of water, (b) the bulk modulus of water at 1 atm, and (c) the speed of sound in water at 1 atm.

1-10

As shown below, a 0.3×0.4 (m^2) plate slides down a long 30° incline on which there is a film of oil 0.5 mm thick with viscosity μ=0.1 kg/m.s. Assuming that the plate does not deform the oil film, estimate:

(a) The terminal sliding velocity (in m/s)

(b) The time required for the plate to accelerate from rest to 99% of the terminal velocity.



1-11

Estimate the viscosity of nitrogen at 86 MPa and 49°C and compare with the measured value of 45 μPa.s.

(86 MPa is high pressure, cannot use “low-density” method)

TABLE A-5

Critical-point constants for common fluids

Substance	Molecular weight	T_c, °R	p_c, atm	μ_c, μPa·s	k_c, mW/(m·K)
H_2	2.016	60.0	12.8	3.47	90.0
He	4.003	9.47	2.26	2.54	20.8
Ar	39.944	272	48.0	26.4	29.8
Air	28.97†	238†	36.4†	19.3†	38.1†
CO_2	44.01	548	72.9	34.3	51.1
CO	28.01	239	34.5	19.0	36.2
N_2	28.02	227	33.5	18.0	36.3
O_2	32.00	278	49.7	25.0	44.1
NO	30.01	324	64	25.8	49.5
N_2O	44.02	557	71.7	33.2	54.9
Cl_2	70.91	751	76.1	42.0	40.7
CH_4	16.04	343	45.8	15.9	66.1

† Values for air are pseudocritical properties computed for the average composition of sea-level dry air.

1-12

Estimate the thermal conductivity of air at 400°C and 1 atm and compare with the measured value of 0.05015 W/(m.K).

Table A-9 Properties of air at 1 atm pressure

Temp. T, °C	Density ρ, kg/m³	Specific Heat c_p J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m²/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m²/s	Prandtl Number Pr
−150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
−100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-6}	5.837×10^{-6}	0.7263
−50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
−40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
−30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
−20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
−10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935
350	0.5664	1056	0.04721	7.892×10^{-5}	3.101×10^{-5}	5.475×10^{-5}	0.6937
400	0.5243	1069	0.05015	8.951×10^{-5}	3.261×10^{-5}	6.219×10^{-5}	0.6948
450	0.4880	1081	0.05298	1.004×10^{-4}	3.415×10^{-5}	6.997×10^{-5}	0.6965
500	0.4565	1093	0.05572	1.117×10^{-4}	3.563×10^{-5}	7.806×10^{-5}	0.6986
600	0.4042	1115	0.06093	1.352×10^{-4}	3.846×10^{-5}	9.515×10^{-5}	0.7037
700	0.3627	1135	0.06581	1.598×10^{-4}	4.111×10^{-5}	1.133×10^{-4}	0.7092
800	0.3289	1153	0.07037	1.855×10^{-4}	4.362×10^{-5}	1.326×10^{-4}	0.7149
900	0.3008	1169	0.07465	2.122×10^{-4}	4.600×10^{-5}	1.529×10^{-4}	0.7206
1000	0.2772	1184	0.07868	2.398×10^{-4}	4.826×10^{-5}	1.741×10^{-4}	0.7260
1500	0.1990	1234	0.09599	3.908×10^{-4}	5.817×10^{-5}	2.922×10^{-4}	0.7478
2000	0.1553	1264	0.11113	5.664×10^{-4}	6.630×10^{-5}	4.270×10^{-4}	0.7539

Note: For ideal gases, the properties *cp*, *k*, μ, and Pr are independent of pressure. The properties r, n, and a at a pressure *P* (in atm) other than 1 atm are determined by multiplying the values of *v* at the given temperature by *P* and by dividing n and a by *P*.

1-13

It is desired to form a gas mixture of 23% CO_2, 14% O_2 and 63% N_2 at 1 atm and 20°C. Estimate the viscosity and thermal conductivity of this mixture.

The constituent properties are as follows:

Constituent	Mole fraction (x)	μ (Pa.s)	K (W/m.K)
CO_2 (44)	0.23	1.37×10^{-5}	0.0146
O_2 (32)	0.14	1.92×10^{-5}	0.0244
N_2 (28)	0.63	1.66×10^{-5}	0.0242

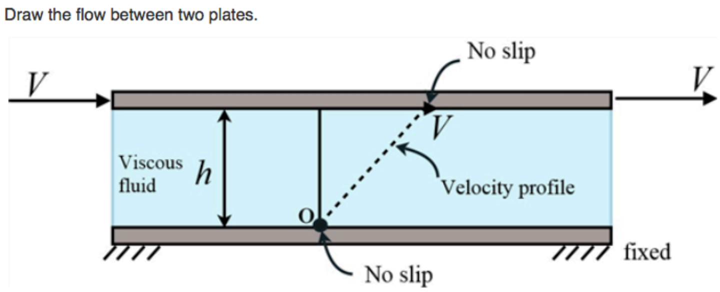
1-14

Some measured values for the viscosity of ammonia gas are as follows:

Temp (K)	300	400	500	600	700	800
μ (Pa.s)	1.03×10^{-5}	1.39×10^{-5}	1.76×10^{-5}	2.10×10^{-5}	2.51×10^{-5}	2.88×10^{-5}

1-15

Analyze the flow between to plates of Figure 1-15 by assuming the fluid is a de Waele power-law fluid as in Eq. 1-31a.
Compute:
(a) The velocity profile $u(y)$ with the power n as a parameter
(b) The velocity at the midpoint $h/2$ for n=0.5, 1.0 and 2.0



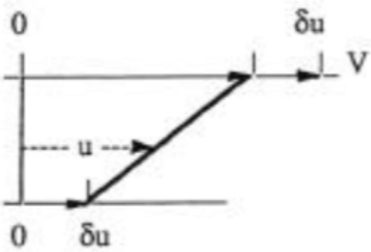
1-16

Repeat the analysis of the velocity profile between two plates (Figure 1-15) for a Newtonian fluid but allow for a slip velocity δu at both walls. Compute the shear stress at both walls. The slip velocity is:

$$\delta u \approx \ell \left(\frac{du}{dy}\right)$$

and shear stress at top wall is

$$\tau_w = \frac{\mu V}{(h + 2\ell)}$$



1-19

From the previous problem, if the temperature, sphere size and velocity remain the same for airflow, at what air pressure will the Reynolds number be equal to 10,000.

1-20

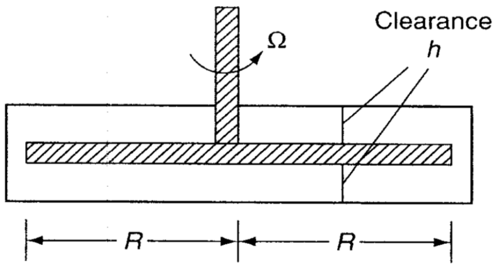
A solid cylinder of mass m, radius R and length L, falls concentrically through a vertical tube of radius R+ΔR, where ΔR ≪ R. The tubes is filled with gas of viscosity μ and mean free path ℓ . Neglect fluid forces on the front and back faces of the cylinder and consider only shear stress in the annular region, assuming a linear velocity profile. Find an analytical expression for the terminal velocity of fall, V, of the cylinder (a) for no slip, (b) with slip (Eq.1-91).

1-21

Oxygen at 20°C and approximately 1200 Pa(abs) flows through a 35 μm diameter smooth capillary tube at an average velocity of 10 cm/s. Estimate the Knudsen number of the flow and whether slip flow will be important.

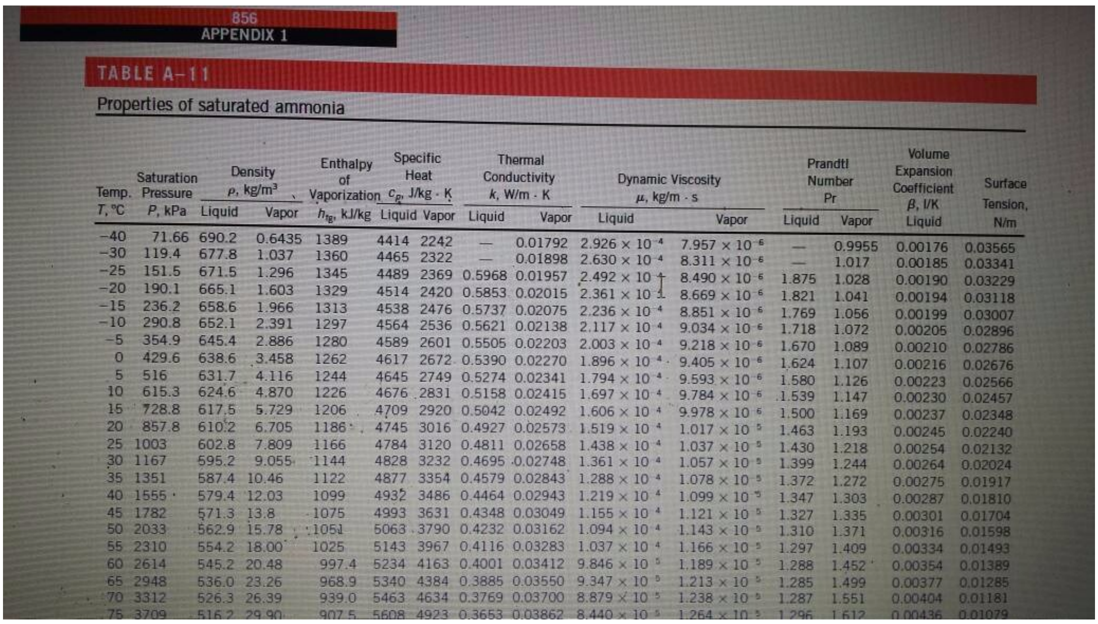
1-22

A disk rotates steadily inside a disk-shaped container filled with oil of viscosity μ. Assume linear velocity profiles with no slip and neglect stress on the outer edges of the disk. Find a formula for the torque M required to drive the disk.



1-23

Show from Eq.1-86, that the coefficient of thermal expansion of a perfect gas is given by $\beta = \frac{1}{T}$. Use this approximation to estimate β of ammonia gas (NH_3) at 20°C and 1 atm and compare with the accepted value from a data reference.



856
APPENDIX 1

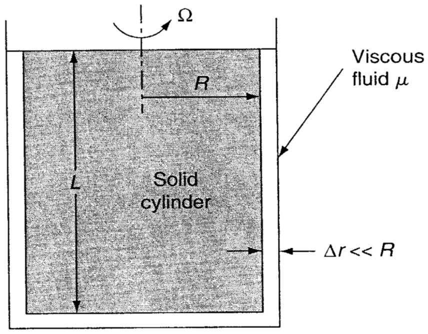
TABLE A-11

Properties of saturated ammonia

Temp. T, °C	Saturation Pressure P, kPa	Density ρ, kg/m³ Liquid	Vapor	Enthalpy of Vaporization h_{fg}, kJ/kg	Specific Heat c_p, J/kg · K Liquid	Vapor	Thermal Conductivity k, W/m · K Liquid	Vapor	Dynamic Viscosity μ, kg/m · s Liquid	Vapor	Prandtl Number Pr Liquid	Vapor	Volume Expansion Coefficient β, 1/K Liquid	Surface Tension, N/m
−40	71.66	690.2	0.6435	1389	4414	2242	—	0.01792	2.926×10^{-4}	7.957×10^{-6}	—	0.9955	0.00176	0.03565
−30	119.4	677.8	1.037	1360	4465	2322	—	0.01898	2.630×10^{-4}	8.311×10^{-6}	—	1.017	0.00185	0.03341
−25	151.5	671.5	1.296	1345	4489	2369	0.5968	0.01957	2.492×10^{-4}	8.490×10^{-6}	1.875	1.028	0.00190	0.03229
−20	190.1	665.1	1.603	1329	4514	2420	0.5853	0.02015	2.361×10^{-4}	8.669×10^{-6}	1.821	1.041	0.00194	0.03118
−15	236.2	658.6	1.966	1313	4538	2476	0.5737	0.02075	2.236×10^{-4}	8.851×10^{-6}	1.769	1.056	0.00199	0.03007
−10	290.8	652.1	2.391	1297	4564	2536	0.5621	0.02138	2.117×10^{-4}	9.034×10^{-6}	1.718	1.072	0.00205	0.02896
−5	354.9	645.4	2.886	1280	4589	2601	0.5505	0.02203	2.003×10^{-4}	9.218×10^{-6}	1.670	1.089	0.00210	0.02786
0	429.6	638.6	3.458	1262	4617	2672	0.5390	0.02270	1.896×10^{-4}	9.405×10^{-6}	1.624	1.107	0.00216	0.02676
5	516	631.7	4.116	1244	4645	2749	0.5274	0.02341	1.794×10^{-4}	9.593×10^{-6}	1.580	1.126	0.00223	0.02566
10	615.3	624.6	4.870	1226	4676	2831	0.5158	0.02415	1.697×10^{-4}	9.784×10^{-6}	1.539	1.147	0.00230	0.02457
15	728.8	617.5	5.729	1206	4709	2920	0.5042	0.02492	1.606×10^{-4}	9.978×10^{-6}	1.500	1.169	0.00237	0.02348
20	857.8	610.2	6.705	1186	4745	3016	0.4927	0.02573	1.519×10^{-4}	1.017×10^{-5}	1.463	1.193	0.00245	0.02240
25	1003	602.8	7.809	1166	4784	3120	0.4811	0.02658	1.438×10^{-4}	1.037×10^{-5}	1.430	1.218	0.00254	0.02132
30	1167	595.2	9.055	1144	4828	3232	0.4695	0.02748	1.361×10^{-4}	1.057×10^{-5}	1.399	1.244	0.00264	0.02024
35	1351	587.4	10.46	1122	4877	3354	0.4579	0.02843	1.288×10^{-4}	1.078×10^{-5}	1.372	1.272	0.00275	0.01917
40	1555	579.4	12.03	1099	4932	3486	0.4464	0.02943	1.219×10^{-4}	1.099×10^{-5}	1.347	1.303	0.00287	0.01810
45	1782	571.3	13.8	1075	4993	3631	0.4348	0.03049	1.155×10^{-4}	1.121×10^{-5}	1.327	1.335	0.00301	0.01704
50	2033	562.9	15.78	1051	5063	3790	0.4232	0.03162	1.094×10^{-4}	1.143×10^{-5}	1.310	1.371	0.00316	0.01598
55	2310	554.2	18.00	1025	5143	3967	0.4116	0.03283	1.037×10^{-4}	1.166×10^{-5}	1.297	1.409	0.00334	0.01493
60	2614	545.2	20.48	997.4	5234	4163	0.4001	0.03412	9.846×10^{-5}	1.189×10^{-5}	1.288	1.452	0.00354	0.01389
65	2948	536.0	23.26	968.9	5340	4384	0.3885	0.03550	9.347×10^{-5}	1.213×10^{-5}	1.285	1.499	0.00377	0.01285
70	3312	526.3	26.39	939.0	5463	4634	0.3769	0.03700	8.879×10^{-5}	1.238×10^{-5}	1.287	1.551	0.00404	0.01181
75	3709	516.2	29.90	907.5	5608	4923	0.3653	0.03862	8.440×10^{-5}	1.264×10^{-5}	1.296	1.612	0.00436	0.01079

1-24

The rotating-cylinder viscometer shears the fluid in a narrow clearance Δr, as shown. Assuming a linear velocity distribution in the gaps, if the driving torque M is measured, find an expression for μ by (a) neglecting the bottom friction and (b) including the bottom friction.



1-25

Consider 1 m^3 of a fluid at 20°C and 1 atm. For an isothermal process, calculate the final density and the energy, in joules, required to compress the fluid until the pressure is 10 atm, for (a) air and (b) water. Discuss the difference in results.

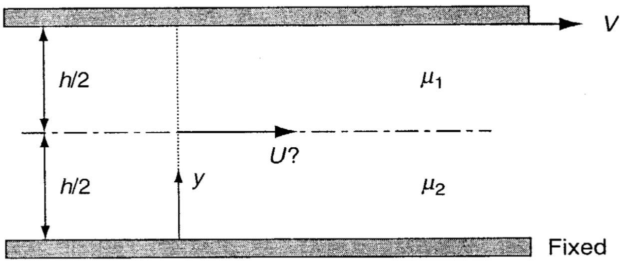
TABLE A-1
Properties of saturated water at atmospheric pressure

Temperature T, °C	Density ρ, kg/m^3	Viscosity μ, mPa · s	Surface tension‡ $\mathcal{T}$, N/m	Vapor pressure p_v, kPa	Bulk modulus K, MPa
0	1000	1.792	0.0757	0.61	2062
20	998	1.002	0.0727	2.34	2230
40	992	0.653	0.0696	7.38	2304
60	983	0.467	0.0662	19.92	2301
80	972	0.355	0.0627	47.35	2235
100	958	0.282	0.0589	101.3	2120
150	915	0.182	0.0488	461	1692
200	863	0.136	0.0377	1580	1190
250	797	0.107	0.0261	3970	716
300	707	0.086	0.0144	8560	342
350	487	0.068	0.0038	16,500	82
374†	315	0.019	0.0	22,100	0

† Critical point.
‡ In contact with air.

1-26

Equal layers of two immiscible fluids are being sheared between a moving and a fixed plate. Assuming linear velocity profiles, find an expression for the interface velocity U as a function of V, μ_1 and μ_2.



1-27

Use the inviscid-flow solution of flow past a cylinder, Eq.1-3, to:

(a) Find the location and value of the maximum fluid acceleration along the cylinder surface. Is your result valid for gases and liquids?

(b) Apply your formula for a_{max} to airflow at 10 m/s past a cylinder of diameter 1 cm and express your result as a ratio compared to the acceleration of gravity. Discuss what your result implies about the ability of fluids to withstand acceleration.