UNIVERSITI SAINS MALAYSIA

Peperiksaan Semester Pertama

Sidang Akademik 1994/95

Oktober/November 1994

EKC 230 - Operasi Unit I

[Masa : 3 Jam]

ARAHAN KEPADA CALON:

Sila pastikan bahawa kertas peperiksaan ini mengandungi **DUA PULUH SATU** (21) muka surat termasuk lampiran yang bercetak sebelum anda memulakan peperiksaan ini.

Kertas soalan ini mengandungi **DUA BAHAGIAN**

Jawab **SATU (1)** soalan dari Bahagian A dan **SEMUA** soalan dari Bahagian B.

Soalan empat (4) dan lima (5) boleh dijawab dalam Bahasa Malaysia atau Bahasa Inggeris dengan sepenuhnya.

BAHAGIAN A

1. Pertimbangkan satu sayap kapalterbang sebagai satu plat yang rata (flat plate) yang berukuran 2.5 m panjang pada arah aliran angin, kapalterbang tersebut sedang bergerak dengan kelajuan 100 m/s di dalam udara yang bertekanan 0.7 bar dan bersuhu - 10°C. Jika bahagian atas sayap tersebut menyerap pancaran suria pada kadar 800 w/m^2, anggarkan suhu sayap tersebut dalam keadaan mantap (steady state temperature). Anggapkan sayap tersebut dibuat dari bahan pejal dan mempunyai suhu yang sekata.

   Data: $\gamma = 19.14 \times 10^{-6}$ m^2/s

   [100 markah]

2. Cecair Freon dialirkan melalui satu tiub Teflon dengan kadar 0.1 kg/s. Tiub tersebut mempunyai garispusat dalam (inside diameter) D_i = 25 mm dan garispusat luar (outside diameter) D_o = 28 mm. Udara pada tekanan atmosfera, kelajuan v = 25 m/s dan suhu 300°K mengalir di luar tiub tersebut. Berapakah kadar pemindahan tenaga per unit panjang tiub tersebut

   (heat transfer per unit length, $\frac{w}{m}$) ke atas freon jika suhu freon 240°K?

   Data: Freon pada suhu 240°K: μ = 3.85 x 10-4 N.S/m^2

   k = 0.069 w/m.k.

   Teflon : k = 0.35 w/m.k.

   [100 markah]

BAHAGIAN B

3. Satu sterika elektrik di rumah (household iron) mempunyai permukaan plat yang diperbuat dari besi keluli (stainless steel) seberat m = 1.5 kg dan luas permukaan A = 0.05 m^2. Pada masa, t = 0, sterika itu dipanaskan dan permukaan plat keluli itu didedahkan kepada keadaan perolakan (exposed to a convection environment):

   (h = 17 watt/m^2°C, T_∞ = 27 °C)

   Kuasa sterika elektrik tersebut ialah P = 500 watt dan suhu permulaan permukaan plat keluli ialah T_i = 27°C.

   (a) Tunjukkan bahawa keadaan 'lumped capacity ' boleh digunakan.

(b) Hasilkan persamaan perbezaan (differential equation) untuk kesimbangan haba tidak mantap (transient heat balance) dengan menggunakan suhu plat, T sebagai angkubah (dependent variable) dan masa t sebagai angkubah bebas (independent variable). Nyatakan keadaan sempadan (boundary condition) untuk persamaan tersebut.

(c) Hasilkan persamaan-persamaan Algebra untuk

$T = f(t)$ dan juga $t = f(T)$.

(d) Berapa lamakah (saat) akan diambil oleh sterika tersebut untuk mencapai suhu 115°C?

(e) Kirakan nombor Fourier (F°) apabila T = 115°C.

Data untuk keluli:

ρ = 7,829 kg/m^3

Cp = 426.7 J/(Kg,°C)

k = 22.5 W/(m,°C).

[100 markah]

4. (a) Nyatakan keadaan-keadaan di mana persamaan yang digunakan untuk plat menegak boleh digunakan untuk silinder menegak untuk pengiraan *h* dalam perolakan.

(b) Pintu menegak ketuhar (oven), 0.5 m tinggi, pada takat suhu 200°C didedahkan kepada udara bersuhu 20°C pada tekanan atmosfera. Anggarkan *hc* (average heat transfer coefficient) pada permukaan pintu ketuhar tersebut. Jika pintu tersebut didedahkan kepada aliran menegak udara secara paksa, kira halaju minimum udara (minimum free stream air velocity) di mana perolakan secara bebas boleh diabaikan.

[100 markah]

5. (a) Lukiskan secara skematik untuk penukar haba 1 kelompang dan 1 tiub (one-shell-pass-one tube pass heat exchanger) untuk aliran selari (cocurrent flow) dan aliran bertentangan (counter flow). Lakarkan juga kesan $(\dot{m}_h Cp)_h$ dan $(\dot{m}_c Cp)_c$ ke atas profil suhu (temperature profile) untuk setiap kes?

(b) Dalam penukar haba 1 kelompang - 1 tiub, bendalir panas masuk pada suhu t_{h_i} = 425 °C dan keluar pada t_{h_o} = 260 °C. Bendalir sejuk pula masuk pada suhu t_{c_i} = 40 °C dan keluar pada t_{c_o} = 150 °C. Kirakan bezaan suhu purata logaritma (log mean temperature difference) sekiranya penukar haba tersebut dikendalikan secara

(i) aliran selari (parallel flow)

(ii) aliran bertentangan (counter flow)

(c) Satu penukar haba diandaikan mempunyai 2 laluan tiub (two-tube-pass) dan digunakan bagi memanaskan 9000 kg_m/h air dari suhu 40°C kepada 120°C. Penukar haba tersebut menggunakan 4500 kgm/h air yang memasuki penukar haba pada takat suhu 315°C untuk pemanasan. Kirakan purata keseluruhan koeffisien pengaliran haba (average overall heat transfer coefficient) untuk penukar haba berkenaan jika jumlah permukaan ialah $5m^2$?

[100 markah]

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APPENDIX

For Laminar free covection past vertical plates

Local Nusselt number

$$Nu_x = 0.478\ Gr_x^{1/4}\ Pr^{1/2}\ (0.861 + Pr)^{1/4}$$

Average Nusselt number

$$Nu_L = 0.637\ Gr^{1/4}\ Pr^{1/2}\ (0.861 + Pr)^{-1/4}$$

For turbulent free convection past plane surfaces Local Nusselt number.

$$Nu_x = 0.0295\ Gr_x^{2/5}\ Pr^{7/15}\ (1 + 0.494\ Pr^{2/3})^{-2/5}$$

Average Nusselt Number

$$Nu_L = 0.246\ Gr_L^{2/5}\ Pr^{7/15}\ (1 + 0.494\ Pr^{2/3})^{-2/5}$$

Working correlations for the convection past Vertical Plane

$$Nu_L = 0.68 + 0.67\ Ra_L^{1/4} = \left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{-4/9} \qquad \textit{for}, o \langle R_{a_L} \langle 10^9$$

$$Nu_L = \left\{0.825 + 0.387\ Ra_L^{1/6}\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{-8/27}\right\}^2 \qquad \textit{for}, 10^9 \langle R_{a_L}$$

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TABLE: PROPERTIES OF AIR AT ATMOSPHERIC PRESSURE

The values of μ, k, Cp and Pr are not strongly pressure-dependent and may be used over a fairly wide range of pressures.

T.K	ρ kg/m^3	Cp kJ/kg°C	μ, kg m.s x 10^5	ν, m^2/s x 10^6	k, Wm°C	α, m^2/s x 10^4	Pr
100	3.6010	1.0266	0.6924	1.923	0.009246	0.02510	0.770
150	2.3675	1.0099	1.0283	4.343	0.013735	0.05745	0.753
200	1.7684	1.0061	1.3289	7.490	0.01809	0.10165	0.739
250	1.4128	1.0053	1.5990	11.31	0.02227	0.15675	0.722
300	1.1774	1.0057	1.8462	15.69	0.02624	0.22160	0.708
350	0.9980	1.0090	2.075	20.76	0.03003	0.2983	0.697
400	0.8826	1.0140	2.286	25.90	0.03365	0.3760	0.689
450	0.7833	1.0207	2.484	31.71	0.03707	0.4222	0.683
500	0.7048	1.0295	2.671	37.90	0.04038	0.5564	0.680
550	0.6423	1.0392	2.848	44.34	0.04360	0.6532	0.680
600	0.5879	1.0551	3.018	51.34	0.04659	0.7512	0.680
650	0.5430	1.0635	3.177	58.51	0.04953	0.8578	0.682
700	0.5030	1.0752	3.332	66.25	0.05230	0.9672	0.684
750	0.4709	1.0856	3.481	73.91	0.05509	1.0774	0.686
800	0.4405	1.0978	3.625	82.29	0.05779	1.1951	0.689
850	0.4149	1.1095	3.765	90.75	0.06028	1.3097	0.692
900	0.3925	1.1212	3.899	99.3	0.06279	1.4271	0.696
950	0.3716	1.1321	4.023	108.2	0.06525	1.5510	0.699
1000	0.3524	1.1417	4.152	117.8	0.06752	1.6779	0.702
1100	0.3204	1.160	4.44	138.6	0.0732	1.969	0.704
1200	0.2947	1.179	4.69	159.1	0.0782	2.251	0.707
1300	0.2707	1.197	4.93	182.1	0.0837	2.583	0.705
1400	0.2515	1.214	5.17	205.5	0.0891	2.920	0.705
1500	0.2355	1.230	5.40	229.1	0.0946	3.262	0.705
1600	0.2211	1.248	5.63	254.5	0.100	3.609	0.705
1700	0.2082	1.267	5.85	280.5	0.105	3.977	0.705
1800	0.1970	1.287	6.07	308.1	0.111	4.379	0.704
1900	0.1858	1.309	6.29	338.5	0.117	4.811	0.704
2000	0.1762	1.338	6.50	369.0	0.124	5.260	0.702
2100	0.1682	1.372	6.72	399.6	0.131	5.715	0.700
2200	0.1602	1.419	6.93	432.6	0.139	6.120	0.707
2300	0.1538	1.482	7.14	464.0	0.149	6.540	0.710
2400	0.1458	1.574	7.35	504.0	0.161	7.020	0.718
2500	0.1394	1.688	7.57	543.5	0.175	7.441	0.730

+ From Natl. Bur. Stand. (U.S.) Circ. 564.1955.

Summary of Equations for Flow over Flat Plates
Properties evaluated at $T_f = (T_w + T_\infty)/2$ unless otherwise noted.

Flow regime	*Restrictions*	*Equation*	*Equation number*
		Heat transfer	
Laminar, local	T_w = const, $Re_x < 5 \times 10^5$ $0.6 < Pr < 50$	$Nu_x = 0.332\, Re_x^{1/2}\, Pr^{1/3}$	(5-44)
Laminar, local	T_w = const, $Re_x < 5 \times 10^5$, $Re_x Pr > 100$	$Nu_x = \dfrac{0.3387\, Re_x^{1/2}\, Pr^{1/3}}{\left[1 + \left(\dfrac{0.0468}{Pr}\right)^{2/3}\right]^{1/4}}$	(5-51)
Laminar, local	q_w = const, $Re_x < 5 \times 10^5$, $0.6 < Pr < 50$	$Nu_x = 0.453\, Re_x^{1/2}\, Pr^{1/3}$	(5-48)
Laminar, local	q_w = const, $Re_x < 5 \times 10^5$	$Nu_x = \dfrac{0.4637\, Re_x^{1/2}\, Pr^{1/3}}{\left[1 + \left(\dfrac{0.0207}{Pr}\right)^{2/3}\right]^{1/4}}$	(5-51)
Laminar, average	$Re_L < 5 \times 10^5$	$\overline{Nu}_L = 2\, Nu_{x=L} = 0.664\, Re_L^{1/2}\, Pr^{1/3}$	(5-46)
Laminar, local	T_w = const, $Re_x < 5 \times 10^5$, $Pr \ll 1$ (liquid metals)	$Nu_x = 0.564 (Re_x Pr)^{1/2}$	
Laminar, local	T_w = const, starting at $x = x_0$, $Re_x < 5 \times 10^5$, $0.6 < Pr < 50$	$Nu_x = 0.332\, Re_x^{1/2}\, Pr^{1/3} \left[1 - \left(\dfrac{x_0}{x}\right)^{3/4}\right]^{-1/3}$	(5-43)
Turbulent, local	T_w = const, $5 \times 10^5 < Re_x < 10^7$	$St_x Pr^{2/3} = 0.0296\, Re_x^{-0.2}$	(5-81)
Turbulent, local	T_w = const, $10^7 < Re_x < 10^9$	$St_x Pr^{2/3} = 0.185 (\log Re_x)^{-2.584}$	(5-82)
Turbulent, local	q_w = const, $5 \times 10^5 < Re_x < 10^7$	$Nu_x = 1.04\, Nu_{x\,T_w = \mathrm{const}}$	(5-87)
Laminar-turbulent, average	T_w = const, $Re_x < 10^7$, $Re_{crit} = 5 \times 10^5$	$\overline{St}\, Pr^{2/3} = 0.037\, Re_L^{-0.2} - 850\, Re_L^{-1}$ $\overline{Nu}_L = Pr^{1/3}(0.037\, Re_L^{0.8} - 850)$	(5-84) (5-85)

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Laminar-turbulent, average	T_w = const, $Re_x < 10^7$, liquids, μ at T_∞, μ_w at T_w	$\overline{Nu}_L = 0.036\,Pr^{0.43}(Re_L^{0.8} - 9200)\left(\frac{\mu_\infty}{\mu_w}\right)^{1/4}$	(5-86)
High-speed flow	T_w = const, $q = hA(T_w - T_{aw})$	Same as for low-speed flow with properties evaluated at $T^* = T_\infty + 0.5(T_w - T_\infty) + 0.22(T_{aw} - T_\infty)$	
		Boundary layer thickness	
Laminar	$Re_x < 5 \times 10^5$	$\frac{\delta}{x} = 5.0\,Re_x^{-1/2}$	(5-21a)
Turbulent	$Re_x < 10^7$ $\delta = 0$ at $x = 0$	$\frac{\delta}{x} = 0.381\,Re_x^{-1/5}$	(5-91)
Turbulent	$5 \times 10^5 < Re_x < 10^7$, $Re_{crit} = 5 \times 10^5$, $\delta = \delta_{lam}$ at Re_{crit}	$\frac{\delta}{x} = 0.381\,Re_x^{-1/5} - 10256\,Re_x^{-1}$	(5-95)
		Friction coefficients	
Laminar, local	$Re_x < 5 \times 10^5$	$C_{fx} = 0.664\,Re_x^{-1/2}$	(5-54)
Turbulent, local	$5 \times 10^5 < Re_x < 10^7$	$C_{fx} = 0.0592\,Re_x^{-1/5}$	(5-77)
Turbulent, local	$10^7 < Re_x < 10^9$	$C_{fx} = 0.370(\log Re_x)^{-2.584}$	(5-78)
Turbulent, average	$Re_{crit} < Re_L < 10^9$	$\overline{C}_f = \frac{0.455}{(\log Re_L)^{2.584}} - \frac{A}{Re_L}$ A from Table 5-1	(5-79)

Summary of Forced-Convection Relations (See text for property evaluation)

Geometry	*Equation*	*Restrictions*	*Equation number*
Tube flow	$\mathrm{Nu}_d = 0.023\,\mathrm{Re}_d^{0.8}\,\mathrm{Pr}^n$	Fully developed turbulent flow $n = 0.4$ for heating $n = 0.3$ for cooling $0.6 < \mathrm{Pr} < 100$	(6-4)
Tube flow	$\mathrm{Nu}_d = 0.027\,\mathrm{Re}_d^{0.8}\,\mathrm{Pr}^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$	Fully developed turbulent flow	(6-5)
Tube flow, entrance region	$\mathrm{Nu}_d = 0.036\,\mathrm{Re}_d^{0.8}\,\mathrm{Pr}^{1/3}\left(\frac{d}{L}\right)^{0.055}$	Turbulent flow, $10 < \frac{L}{d} < 400$	(6-6)
Tube flow	Petukov relation	Fully developed turbulent flow, $0.5 < \mathrm{Pr} < 2000$, $10^4 < \mathrm{Re}_d < 5 \times 10^6$, $0 < \frac{\mu_b}{\mu_w} < 40$	(6-7)
Tube flow	$\mathrm{Nu}_d = 3.66 + \frac{0.0668(d/L)\,\mathrm{Re}_d\,\mathrm{Pr}}{1 + 0.04[(d/L)\,\mathrm{Re}_d\,\mathrm{Pr}]^{2/3}}$	Laminar	(6-9)
Tube flow	$\mathrm{Nu}_d = 1.86\,(\mathrm{Re}_d\,\mathrm{Pr})^{1/3}\left(\frac{d}{L}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$	Fully developed laminar flow, $\mathrm{Re}_d\,\mathrm{Pr}\,\frac{d}{L} > 10$	(6-10)
Rough tubes	$\mathrm{St}_b\,\mathrm{Pr}_f^{2/3} = \frac{f}{8}$ or Eq. (6-7)	Fully developed turbulent flow	(6-12)

Noncircular ducts	Reynolds number evaluated on basis of hydraulic diameter $D_H = \frac{4A}{P}$	Same as particular equation for tube flow	(6-14)
Flow across cylinders	$\mathrm{Nu}_f = C\,\mathrm{Re}_{df}^{n}\,\mathrm{Pr}^{1/3}$ C and n from Table 6-2	$0.4 < \mathrm{Re}_{df} < 400{,}000$	(6-17)
Flow across cylinders	$\mathrm{Nu}_{df} = 0.3 + \frac{0.62\,\mathrm{Re}_f^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1 + \left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{1/4}}\left[1 + \left(\frac{\mathrm{Re}_f}{282{,}000}\right)^{5/8}\right]^{4/5}$	$10^2 < \mathrm{Re}_f < 10^7$, $\mathrm{Pe} > 0.2$	(6-21)
Flow across cylinders		See text	(6-18) to (6-20) (6-22) to (6-24)
Flow across noncircular cylinders	See Table 6-3		
Flow across spheres		See text	(6-25) to (6-30)
Flow across tube banks	$\mathrm{Nu}_f = C\,\mathrm{Re}_{f,\max}^{n}\,\mathrm{Pr}_f^{n}$ C and n from Table 6-4	See text	(6-17)
Flow across tube banks	$\mathrm{Nu} = C\,\mathrm{Re}_{d,\max}^{n}\,\mathrm{Pr}^{0.36}\left(\frac{\mathrm{Pr}}{\mathrm{Pr}_w}\right)^{1/4}$	$0.7 < \mathrm{Pr} < 500$ $10 < \mathrm{Re}_{d,\max} < 10^6$	(6-34)
Liquid metals		See text	(6-37) to (6-48)

Table A-2 Property Values for Metals†

Metal	Properties at 20°C				Thermal conductivity k, W/m · °C									
	ρ, kg/m^3	c_p, kJ/kg · °C	k, W/m · °C	α, m^2/s × 10^5	− 100°C − 148°F	0°C 32°F	100°C 212°F	200°C 392°F	300°C 572°F	400°C 752°F	600°C 1112°F	800°C 1472°F	1000°C 1832°F	1200°C 2192°F
Aluminum:														
Pure	2,707	0.896	204	8.418	215	202	206	215	228	249				
Al-Cu (Duralumin), 94–96% Al, 3–5% Cu, trace Mg	2,787	0.883	164	6.676	126	159	182	194						
Al-Si (Silumin, copper-bearing), 86.5% Al, 1% Cu	2,659	0.867	137	5.933	119	137	144	152	161					
Al-Si (Alusil), 78–80% Al, 20–22% Si	2,627	0.854	161	7.172	144	157	168	175	178					
Al-Mg-Si, 97% Al, 1% Mg, 1% Si, 1% Mn	2,707	0.892	177	7.311		175	189	204						
Lead	11,373	0.130	35	2.343	36.9	35.1	33.4	31.5	29.8					
Iron:														
Pure	7,897	0.452	73	2.034	87	73	67	62	55	48	40	36	35	36
Wrought iron, 0.5% C	7,849	0.46	59	1.626		59	57	52	48	45	36	33	33	33
Steel (C max ≈ 1.5%):														
Carbon steel														
C ≈ 0.5%	7,833	0.465	54	1.474		55	52	48	45	42	35	31	29	31
1.0%	7,801	0.473	43	1.172		43	43	42	40	36	33	29	28	29
1.5%	7,753	0.486	36	0.970		36	36	36	35	33	31	28	28	29
Nickel steel														
Ni ≈ 0%	7,897	0.452	73	2.026										
20%	7,933	0.46	19	0.526										

Table A-2 Property Values for Metals† (*continued*)

Metal	Properties at 20°C ρ, kg/m³	c_p, kJ/kg · °C	k, W/m · °C	α, m²/s × 10⁵	Thermal conductivity k, W/m · °C −100°C −148°F	0°C 32°F	100°C 212°F	200°C 392°F	300°C 572°F	400°C 752°F	600°C 1112°F	800°C 1472°F	1000°C 1832°F	1200°C 2192°F
40%	8,169	0.46	10	0.279										
80%	8,618	0.46	35	0.872										
Invar 36% Ni	8,137	0.46	10.7	0.286										
Chrome steel														
Cr = 0%	7,897	0.452	73	2.026	87	73	67	62	55	48	40	36	35	32 36
1%	7,865	0.46	61	1.665		62	55	52	47	42	36	33	33	
5%	7,833	0.46	40	1.110		40	38	36	36	33	29	29	29	
20%	7,689	0.46	22	0.635		22	22	22	22	24	24	26	29	
Cr-Ni(chrome-nickel): 15% Cr, 10% Ni	7,865	0.46	19	0.527										
18% Cr, 8% Ni (V2A)	7,817	0.46	16.3	0.444		16.3	17	17	19	19	22	27	31	
20% Cr, 15% Ni	7,833	0.46	15.1	0.415										
25% Cr, 20% Ni	7,865	0.46	12.8	0.361										
Tungsten steel														
W = 0%	7,897	0.452	73	2.026										
1%	7,913	0.448	66	1.858										
5%	8,073	0.435	54	1.525										
10%	8,314	0.419	48	1.391										
Copper:														
Pure	8,954	0.3831	386	11.234	407	386	379	374	369	363	353			

Aluminum bronze 95% Cu, 5% Al	8,666	0.410	83	2.330										
Bronze 75% Cu, 25% Sn	8,666	0.343	26	0.859										
Red brass 85% Cu, 9% Sn, 6% Zn	8,714	0.385	61	1.804		59	71							
Brass 70% Cu, 30% Zn	8,522	0.385	111	3.412	88		128	144	147	147				
German silver 62% Cu, 15% Ni, 22% Zn	8,618	0.394	24.9	0.733	19.2		31	40	45	48				
Constantan 60% Cu, 40% Ni	8,922	0.410	22.7	0.612	21		22.2	26						
Magnesium:														
Pure	1,746	1.013	171	9.708	178	171	168	163	157					
Mg-Al (electrolytic) 6–8% Al, 1–2% Zn	1,810	1.00	66	3.605		52	62	74	83					
Molybdenum	10,220	0.251	123	4.790	138	125	118	114	111	109	106	102	99	92
Nickel:														
Pure (99.9%)	8,906	0.4459	90	2.266	104	93	83	73	64	59				
Ni-Cr 90% Ni, 10% Cr	8.666	0.444	17	0.444		17.1	18.9	20.9	22.8	24.6				
80% Ni, 20% Cr	8,314	0.444	12.6	0.343		12.3	13.8	15.6	17.1	18.0	22.5			
Silver:														
Purest	10,524	0.2340	419	17.004	419	417	415	412						
Pure (99.9%)	10,525	0.2340	407	16.563	419	410	415	374	362	360				
Tin, pure	7,304	0.2265	64	3.884	74	65.9	59	57						
Tungsten	19,350	0.1344	163	6.271		166	151	142	133	126	112	76		
Zinc, pure	7,144	0.3843	112.2	4.106	114	112	109	106	100	93				

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†Adapted to SI units from E. R. G. Eckert and R. M. Drake, "Heat and Mass Transfer," 2d ed., McGraw-Hill Book Company, New York, 1959.

Table A-3 Properties of Nonmetals†

Substance	*Temperature*, °C	*k*, W/m · °C	*ρ*, kg/m³	*c*, kJ/kg · °C	*α*, m²/s × 1
		Structural and heat-resistant materials			
Asphalt	20–55	0.74–0.76			
Brick:					
Building brick, common	20	0.69	1600	0.84	5.2
Face		1.32	2000		
Carborundum brick	600	18.5			
	1400	11.1			
Chrome brick	200	2.32	3000	0.84	9.2
	550	2.47			9.8
	900	1.99			7.9
Diatomaceous earth, molded and fired	200	0.24			
	870	0.31			
Fireclay brick, burnt 2426°F	500	1.04	2000	0.96	5.4
	800	1.07			
	1100	1.09			
Burnt 2642°F	500	1.28	2300	0.96	5.8
	800	1.37			
	1100	1.40			
Missouri	200	1.00	2600	0.96	4.0
	600	1.47			
	1400	1.77			
Magnesite	200	3.81		1.13	
	650	2.77			
	1200	1.90			
Cement, portland		0.29	1500		
Mortar	23	1.16			
Concrete, cinder	23	0.76			
Stone, 1-2-4 mix	20	1.37	1900–2300	0.88	8.2–6
Glass, window	20	0.78 (avg)	2700	0.84	3.4
Corosilicate	30–75	1.09	2200		
Plaster, gypsum	20	0.48	1440	0.84	4.0
Metal lath	20	0.47			
Wood lath	20	0.28			
Stone:					
Granite		1.73–3.98	2640	0.82	8–1
Limestone	100–300	1.26–1.33	2500	0.90	5.6–5
Marble		2.07–2.94	2500–2700	0.80	10–1
Sandstone	40	1.83	2160–2300	0.71	11.2–1
Wood (across the grain):					
Balsa, 8.8 lb/ft³	30	0.055	140		
Cypress	30	0.097	460		
Fir	23	0.11	420	2.72	0.96
Maple or oak	30	34 0.166	540	2.4	1.28
Yellow pine	23	0.147	640	2.8	0.82
White pine	30	0.112	430		

Table A-3 Properties of Nonmetals† (continued)

Substance	Temperature, °C	k, W/m · °C	ρ, kg/m³	c, kJ/kg · °C	α, m²/s × 10⁷
	Insulating material				
Asbestos:					
Loosely packed	−45	0.149			
	0	0.154	470–570	0.816	3.3–4
	100	0.161			
Asbestos-cement boards	20	0.74			
Sheets	51	0.166			
Felt, 40 laminations/in	38	0.057			
	150	0.069			
	260	0.083			
20 laminations/in	38	0.078			
	150	0.095			
	260	0.112			
Corrugated, 4 plies/in	38	0.087			
	93	0.100			
	150	0.119			
Asbestos cement	—	2.08			
Balsam wool, 2.2 lb/ft³	32	0.04	35		
Cardboard, corrugated	—	0.064			
Celotex	32	0.048			
Corkboard, 10 lb/ft³	30	0.043	160		
Cork, regranulated	32	0.045	45–120	1.88	2–5.3
Ground	32	0.043	150		
Diatomaceous earth (Sil-o-cel)	0	0.061	320		
Felt, hair	30	0.036	130–200		
Wool	30	0.052	330		
Fiber, insulating board	20	0.048	240		
Glass wool, 1.5 lb/ft³	23	0.038	24	0.7	22.6
Insulex, dry	32	0.064			
		0.144			
Kapok	30	0.035			
Magnesia, 85%	38	0.067	270		
	93	0.071			
	150	0.074			
	204	0.080			
Rock wool, 10 lb/ft³	32	0.040	160		
Loosely packed	150	0.067	64		
	260	0.087			
Sawdust	23	0.059			
Silica aerogel	32	0.024	140		
Wood shavings	23	0.059			

†Adapted to SI units from A. I. Brown and S. M. Marco, "Introduction to Heat Transfer," 3d ed., McGraw-Hill Book Company, New York, 1958.

Table A-4 Properties of Saturated Liquids†

T, °C	ρ, kg/m³	c_p, kJ/kg · °C	ν, m²/s	k, W/m · °C	α, m²/s	Pr	β, K⁻¹
				Ammonia, NH_3			
−50	703.69	4.463	0.435×10^{-6}	0.547	1.742×10^{-7}	2.60	
−40	691.68	4.467	0.406	0.547	1.775	2.28	
−30	679.34	4.476	0.387	0.549	1.801	2.15	
−20	666.69	4.509	0.381	0.547	1.819	2.09	
−10	653.55	4.564	0.378	0.543	1.825	2.07	
0	640.10	4.635	0.373	0.540	1.819	2.05	
10	626.16	4.714	0.368	0.531	1.801	2.04	
20	611.75	4.798	0.359	0.521	1.775	2.02	2.45×10^{-3}
30	596.37	4.890	0.349	0.507	1.742	2.01	
40	580.99	4.999	0.340	0.493	1.701	2.00	
50	564.33	5.116	0.330	0.476	1.654	1.99	
				Carbon dioxide, CO_2			
−50	1.156.34	1.84	0.119×10^{-6}	0.0855	0.4021×10^{-7}	2.96	
−40	1.117.77	1.88	0.118	0.1011	0.4810	2.46	
−30	1.076.76	1.97	0.117	0.1116	0.5272	2.22	
−20	1.032.39	2.05	0.115	0.1151	0.5445	2.12	
−10	983.38	2.18	0.113	0.1099	0.5133	2.20	
0	926.99	2.47	0.108	0.1045	0.4578	2.38	
10	860.03	3.14	0.101	0.0971	0.3608	2.80	
20	772.57	5.0	0.091	0.0872	0.2219	4.10	14.00×10^{-3}
30	597.81	36.4	0.080	0.0703	0.0279	28.7	
				Sulfur dioxide, SO_2			
−50	1,560.84	1.3595	0.484×10^{-6}	0.242	1.141×10^{-7}	4.24	
−40	1,536.81	1.3607	0.424	0.235	1.130	3.74	
−30	1,520.64	1.3616	0.371	0.230	1.117	3.31	
−20	1,488.60	1.3624	0.324	0.225	1.107	2.93	
−10	1,463.61	1.3628	0.288	0.218	1.097	2.62	
0	1,438.46	1.3636	0.257	0.211	1.081	2.38	
10	1,412.51	1.3645	0.232	0.204	1.066	2.18	
20	1,386.40	1.3653	0.210	0.199	1.050	2.00	1.94×10^{-3}
30	1,359.33	1.3662	0.190	0.192	1.035	1.83	
40	1,329.22	1.3674	0.173	0.185	1.019	1.70	
50	1,299.10	1.3683	0.162	0.177	0.999	1.61	

Table A-4 Properties of Saturated Liquids† *(continued)*

T, °C	ρ, kg/m^3	c_p, kJ/kg · °C	ν, m^2/s	k, W/m · °C	α, m^2/s	Pr	β, K^{-1}
Dichlorodifluoromethane (Freon), CCl_2F_2							
−50	1,546.75	0.8750	0.310 × 10^{-6}	0.067	0.501 × 10^{-7}	6.2	2.63 × 10^{-3}
−40	1,518.71	0.8847	0.279	0.069	0.514	5.4	
−30	1,489.56	0.8956	0.253	0.069	0.526	4.8	
−20	1,460.57	0.9073	0.235	0.071	0.539	4.4	
−10	1,429.49	0.9203	0.221	0.073	0.550	4.0	
0	1,397.45	0.9345	0.214 × 10^{-6}	0.073	0.557 × 10^{-7}	3.8	
10	1,364.30	0.9496	0.203	0.073	0.560	3.6	
20	1,330.18	0.9659	0.198	0.073	0.560	3.5	
30	1,295.10	0.9835	0.194	0.071	0.560	3.5	
40	1,257.13	1.0019	0.191	0.069	0.555	3.5	
50	1,215.96	1.0216	0.190	0.067	0.545	3.5	
Glycerin, $C_3H_5(OH)_3$							
0	1,276.03	2.261	0.00831	0.282	0.983 × 10^{-7}	84.7 × 10^{3}	
10	1,270.11	2.319	0.00300	0.284	0.965	31.0	
20	1,264.02	2.386	0.00118	0.286	0.947	12.5	0.50 × 10^{-3}
30	1,258.09	2.445	0.00050	0.286	0.929	5.38	
40	1,252.01	2.512	0.00022	0.286	0.914	2.45	
50	1,244.96	2.583	0.00015	0.287	0.893	1.63	
Ethylene glycol, $C_2H_4(OH)_2$							
0	1,130.75	2.294	57.53 × 10^{-6}	0.242	0.934 × 10^{-7}	615	
20	1,116.65	2.382	19.18	0.249	0.939	204	0.65 × 10^{-3}
40	1,101.43	2.474	8.69	0.256	0.939	93	
60	1,087.66	2.562	4.75	0.260	0.932	51	
80	1,077.56	2.650	2.98	0.261	0.921	32.4	
100	1,058.50	2.742	2.03	0.263	0.908	22.4	
Engine oil (unused)							
0	899.12	1.796	0.00428	0.147	0.911 × 10^{-7}	47,100	
20	888.23	1.880	0.00090	0.145	0.872	10,400	0.70 × 10^{-3}
40	876.05	1.964	0.00024	0.144	0.834	2,870	
60	864.04	2.047	0.839 × 10^{-4}	0.140	0.800	1,050	
80	852.02	2.131	0.375	0.138	0.769	490	
100	840.01	2.219	0.203	0.137	0.738	276	
120	828.96	2.307	0.124	0.135	0.710	175	
140	816.94	2.395	0.080	0.133	0.686	116	
160	805.89	2.483	0.056	0.132	0.663	84	

Table A-4 Properties of Saturated Liquids† *(continued)*

T, °C	ρ, kg/m^3	c_p, kJ/kg · °C	ν, m^2/s	k, W/m · °C	α, m^2/s	Pr	β, K^{-1}
			Mercury, Hg				
0	13,628.22	0.1403	0.124×10^{-6}	8.20	42.99×10^{7}	0.0288	
20	13,579.04	0.1394	0.114	8.69	46.06	0.0249	1.82×10^{-4}
50	13,505.84	0.1386	0.104	9.40	50.22	0.0207	
100	13,384.58	0.1373	0.0928	10.51	57.16	0.0162	
150	13,264.28	0.1365	0.0853	11.49	63.54	0.0134	
200	13,144.94	0.1570	0.0802	12.34	69.08	0.0116	
250	13,025.60	0.1357	0.0765	13.07	74.06	0.0103	
315.5	12,847	0.134	0.0673	14.02	81.5	0.0083	

†Adapted to SI units from E. R. G. Eckert and R. M. Drake, "Heat and Mass Transfer," 2d ed., McGraw-Hill Book Company, New York, 1959.

Table A-5 Properties of Air at Atmospheric Pressure†

The values of μ, k, c_p, and Pr are not strongly pressure-dependent and may be used over a fairly wide range of pressures.

T, K	ρ kg/m^3	c_p, kJ/kg · °C	μ, kg/m · s × 10^5	ν, m^2/s × 10^6	k, W/m · °C	α, m^2/s × 10^4	Pr
100	3.6010	1.0266	0.6924	1.923	0.009246	0.02501	0.770
150	2.3675	1.0099	1.0283	4.343	0.013735	0.05745	0.753
200	1.7684	1.0061	1.3289	7.490	0.01809	0.10165	0.739
250	1.4128	1.0053	1.5990	11.31	0.02227	0.15675	0.722
300	1.1774	1.0057	1.8462	15.69	0.02624	0.22160	0.708
350	0.9980	1.0090	2.075	20.76	0.03003	0.2983	0.697
400	0.8826	1.0140	2.286	25.90	0.03365	0.3760	0.689
450	0.7833	1.0207	2.484	31.71	0.03707	0.4222	0.683
500	0.7048	1.0295	2.671	37.90	0.04038	0.5564	0.680
550	0.6423	1.0392	2.848	44.34	0.04360	0.6532	0.680
600	0.5879	1.0551	3.018	51.34	0.04659	0.7512	0.680
650	0.5430	1.0635	3.177	58.51	0.04953	0.8578	0.682
700	0.5030	1.0752	3.332	66.25	0.05230	0.9672	0.684
750	0.4709	1.0856	3.481	73.91	0.05509	1.0774	0.686
800	0.4405	1.0978	3.625	82.29	0.05779	1.1951	0.689
850	0.4149	1.1095	3.765	90.75	0.06028	1.3097	0.692
900	0.3925	1.1212	3.899	99.3	0.06279	1.4271	0.696
950	0.3716	1.1321	4.023	108.2	0.06525	1.5510	0.699
1000	0.3524	1.1417	4.152	117.8	0.06752	1.6779	0.702
1100	0.3204	1.160	4.44	138.6	0.0732	1.969	0.704
1200	0.2947	1.179	4.69	159.1	0.0782	2.251	0.707
1300	0.2707	1.197	4.93	182.1	0.0837	2.583	0.705
1400	0.2515	1.214	5.17	205.5	0.0891	2.920	0.705
1500	0.2355	1.230	5.40	229.1	0.0946	3.262	0.705
1600	0.2211	1.248	5.63	254.5	0.100	3.609	0.705
1700	0.2082	1.267	5.85	280.5	0.105	3.977	0.705
1800	0.1970	1.287	6.07	308.1	0.111	4.379	0.704
1900	0.1858	1.309	6.29	338.5	0.117	4.811	0.704
2000	0.1762	1.338	6.50	369.0	0.124	5.260	0.702
2100	0.1682	1.372	6.72	399.6	0.131	5.715	0.700
2200	0.1602	1.419	6.93	432.6	0.139	6.120	0.707
2300	0.1538	1.482	7.14	464.0	0.149	6.540	0.710
2400	0.1458	1.574	7.35	504.0	0.161	7.020	0.718
2500	0.1394	1.688	7.57	543.5	0.175	7.441	0.730

†From *Natl. Bur. Stand. (U.S.) Circ.* 564, 1955.

Table A-6 Properties of Gases at Atmospheric Pressure†

Values of μ, k, c_p, and Pr are not strongly pressure-dependent for He, H_2, O_2, and N_2 and may be used over a fairly wide range of pressures.

T, K	ρ, kg/m³	c_p, kJ/kg · °C	μ, kg/m · s	ν, m²/s	k, W/m · °C	α, m²/s	Pr
				Helium			
144	0.3379	5.200	125.5×10^{-7}	37.11×10^{-6}	0.0928	0.5275×10^{-4}	0.70
200	0.2435	5.200	156.6	64.38	0.1177	0.9288	0.694
255	0.1906	5.200	181.7	95.50	0.1357	1.3675	0.70
366	0.13280	5.200	230.5	173.6	0.1691	2.449	0.71
477	0.10204	5.200	275.0	269.3	0.197	3.716	0.72
589	0.08282	5.200	311.3	375.8	0.225	5.215	0.72
700	0.07032	5.200	347.5	494.2	0.251	6.661	0.72
800	0.06023	5.200	381.7	634.1	0.275	8.774	0.72
				Hydrogen			
150	0.16371	12.602	5.595×10^{-6}	34.18×10^{-6}	0.0981	0.475×10^{-4}	0.718
200	0.12270	13.540	6.813	55.53	0.1282	0.772	0.719
250	0.09819	14.059	7.919	80.64	0.1561	1.130	0.713
300	0.08185	14.314	8.963	109.5	0.182	1.554	0.706
350	0.07016	14.436	9.954	141.9	0.206	2.031	0.697
400	0.06135	14.491	10.864	177.1	0.228	2.568	0.690
450	0.05462	14.499	11.779	215.6	0.251	3.164	0.682
500	0.04918	14.507	12.636	257.0	0.272	3.817	0.675
550	0.04469	14.532	13.475	301.6	0.292	4.516	0.668
600	0.04085	14.537	14.285	349.7	0.315	5.306	0.664
700	0.03492	14.574	15.89	455.1	0.351	6.903	0.659
800	0.03060	14.675	17.40	569	0.384	8.563	0.664
900	0.02723	14.821	18.78	690	0.412	10.217	0.676
				Oxygen			
150	2.6190	0.9178	11.490×10^{-6}	4.387×10^{-6}	0.01367	0.05688×10^{-4}	0.773
200	1.9559	0.9131	14.850	7.593	0.01824	0.10214	0.745
250	1.5618	0.9157	17.87	11.45	0.02259	0.15794	0.725
300	1.3007	0.9203	20.63	15.86	0.02676	0.22353	0.709
350	1.1133	0.9291	23.16	20.80	0.03070	0.2968	0.702
400	0.9755	0.9420	25.54	26.18	0.03461	0.3768	0.695
450	0.8682	0.9567	27.77	31.99	0.03828	0.4609	0.694
500	0.7801	0.9722	29.91	38.34	0.04173	0.5502	0.697
550	0.7096	0.9881	31.97	45.05	0.04517	0.641	0.700

Table A-6 Properties of Gases at Atmospheric Pressure† (continued)
Values of μ, k, c_p, and Pr are not strongly pressure-dependent for He, H_2, O_2, and N_2 and may be used over a fairly wide range of pressures.

T, K	ρ, kg/m³	c_p, kJ/kg · °C	μ, kg/m · s	ν, m²/s	k, W/m · °C	α, m²/s	Pr
				Nitrogen			
200	1.7108	1.0429	12.947×10^{-6}	7.568×10^{-6}	0.01824	0.10224×10^{-4}	0.747
300	1.1421	1.0408	17.84	15.63	0.02620	0.22044	0.713
400	0.8538	1.0459	21.98	25.74	0.03335	0.3734	0.691
500	0.6824	1.0555	25.70	37.66	0.03984	0.5530	0.684
600	0.5687	1.0756	29.11	51.19	0.04580	0.7486	0.686
700	0.4934	1.0969	32.13	65.13	0.05123	0.9466	0.691
800	0.4277	1.1225	34.84	81.46	0.05609	1.1685	0.700
900	0.3796	1.1464	37.49	91.06	0.06070	1.3946	0.711
1000	0.3412	1.1677	40.00	117.2	0.06475	1.6250	0.724
1100	0.3108	1.1857	42.28	136.0	0.06850	1.8591	0.736
1200	0.2851	1.2037	44.50	156.1	0.07184	2.0932	0.748
				Carbon dioxide			
220	2.4733	0.783	11.105×10^{-6}	4.490×10^{-6}	0.010805	0.05920×10^{-4}	0.818
250	2.1657	0.804	12.590	5.813	0.012884	0.07401	0.793
300	1.7973	0.871	14.958	8.321	0.016572	0.10588	0.770
350	1.5362	0.900	17.205	11.19	0.02047	0.14808	0.755
400	1.3424	0.942	19.32	14.39	0.02461	0.19463	0.738
450	1.1918	0.980	21.34	17.90	0.02897	0.24813	0.721
500	1.0732	1.013	23.26	21.67	0.03352	0.3084	0.702
550	0.9739	1.047	25.08	25.74	0.03821	0.3750	0.685
600	0.8938	1.076	26.83	30.02	0.04311	0.4483	0.668
				Ammonia, NH_3			
273	0.7929	2.177	9.353×10^{-6}	1.18×10^{-5}	0.0220	0.1308×10^{-4}	0.90
323	0.6487	2.177	11.035	1.70	0.0270	0.1920	0.88
373	0.5590	2.236	12.886	2.30	0.0327	0.2619	0.87
423	0.4934	2.315	14.672	2.97	0.0391	0.3432	0.87
473	0.4405	2.395	16.49	3.74	0.0467	0.4421	0.84
				Water vapor			
380	0.5863	2.060	12.71×10^{-6}	2.16×10^{-5}	0.0246	0.2036×10^{-4}	1.060
400	0.5542	2.014	13.44	2.42	0.0261	0.2338	1.040
450	0.4902	1.980	15.25	3.11	0.0299	0.307	1.010
500	0.4405	1.985	17.04	3.86	0.0339	0.387	0.996
550	0.4005	1.997	18.84	4.70	0.0379	0.475	0.991
600	0.3652	2.026	20.67	5.66	0.0422	0.573	0.986
650	0.3380	2.056	22.47	6.64	0.0464	0.666	0.995
700	0.3140	2.085	24.26	7.72	0.0505	0.772	1.000
750	0.2931	2.119	26.04	8.88	0.0549	0.883	1.005
800	0.2739	2.152	27.86	10.20	0.0592	1.001	1.010
850	0.2579	2.186	29.69	11.52	0.0637	1.130	1.019

†Adapted to SI units from E. R. G. Eckert and R. M. Drake, "Heat and Mass Transfer," 2nd ed., McGraw-Hill Book Company, New York, 1959.