SULIT

KEMENTERIAN PENDIDIKAN TINGGI
JABATAN PENDIDIKAN POLITEKNIK DAN KOLEJ KOMUNITI

BAHAGIAN PEPERIKSAAN DAN PENILAIAN
JABATAN PENDIDIKAN POLITEKNIK DAN KOLEJ KOMUNITI
KEMENTERIAN PENDIDIKAN TINGGI

JABATAN KEJURUTERAAN PETROKIMIA

PEPERIKSAAN AKHIR

SESI II : 2022/2023

DGP30122 : HEAT TRANSFER

TARIKH : 7 JUN 2023
MASA : 8.30 PG - 10.30 PG (2 JAM)

Kertas ini mengandungi **SEMBILAN (9)** halaman bercetak.

Struktur (4 soalan)

Dokumen sokongan yang disertakan : Jadual, Formula

JANGAN BUKA KERTAS SOALAN INI SEHINGGA DIARAHKAN

(CLO yang tertera hanya sebagai rujukan)

SULIT

INSTRUCTION:

This section consists of **FOUR (4)** structured questions. Answer **ALL** questions.

ARAHAN:

*Bahagian ini mengandungi **EMPAT (4)** soalan berstruktur. Jawab **SEMUA** soalan.*

QUESTION 1

SOALAN 1

CLO1 (a) Heat transfer is a discipline of thermal engineering that concerns the generation, use, conversion, and exchange of thermal energy between physical systems.

Pemindahan haba ialah satu disiplin kejuruteraan haba yang melibatkan penjanaan, penggunaan, penukaran, dan pertukaran tenaga haba antara sistem fizikal.

(i) Define heat and energy.

Takrifkan haba dan tenaga.

[2 marks]

[2 *markah*]

(ii) Define **TWO (2)** mechanisms of heat transfer.

*Takrifkan DUA **(2)** mekanisme pemindahan haba.*

[4 marks]

[4 *markah*]

CLO1 (b) Explain the relation between the rate of heat conduction through a layer to the area, the thickness and the temperature difference across the layer.

Terangkan hubungkait diantara kadar konduksi haba menerusi suatu lapisan kepada luas permukaan, ketebalan dan perbezaan suhu lapisan tersebut.

[4 marks]

[4 *markah*]

CLO2 (c) Consider a 5 m high, 8 m long and 0.22m thick wall whose representative cross section as given in the **Figure 1(c)**. The thermal conductivities of various materials used in W/m ·°C are $K_A = K_F = 2$, $K_B = 8$, $K_C = 20$, $K_D = 15$, $K_E = 35$. The left and right surfaces of the wall are maintained at uniform temperatures of 300°C and 100°C, respectively. Assuming heat transfer through the wall to be one-dimensional.

Pertimbangkan tembok setinggi 5 m, panjang 8 m dan tebal 0.22 m yang garis lintangnya mewakili seperti yang ditunjukkan dalam Rajah 1(c). Kekonduksian terma pelbagai bahan yang digunakan dalam W / m · ° C adalah $K_A = K_F = 2$, $K_B = 8$, $K_C = 20$, $K_D = 15$, $K_E = 35$. Permukaan kiri dan kanan dinding pada suhu seragam masing-masing 300°C dan 100 °C. Dengan andaian pemindahan haba melalui dinding menjadi satu dimensi.

(i) Calculate the thermal resistance total, R_{total}.
Kirakan jumlah rangkaian rintangan terma, R_{jumlah}.

[7 marks]
[7 *markah*]

(ii) Calculate the rate of heat transfer through the wall.
Kirakan kadar pemindahan haba melalui dinding.

[8 marks]
[8 *markah*]

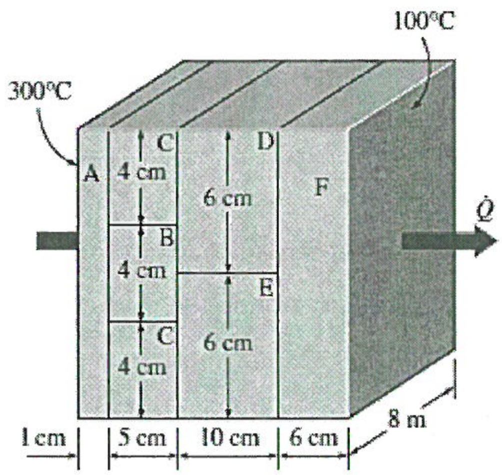


Figure 1(c) / *Rajah 1(c)*

QUESTION 2
SOALAN 2

CLO1 (a) Define laminar and turbulent flow.
Takrifkan aliran lamina dan aliran bergelora.

[4 marks]
[4 *markah*]

CLO1 (b) The mechanism of convection is the transfer of heat energy by actual physical movement of fluid molecule from one place to another in which there exists a temperature gradient.
Mekanisme perolakan ialah pemindahan tenaga haba melalui pergerakan fizikal sebenar molekul bendalir dari satu tempat ke tempat lain di mana terdapat perbezaan suhu.

(i) Explain the convection mechanism as shown in **Figure 2(b).**
Terangkan mekanisme perolakan seperti yang ditujukkan pada ***Rajah 2(b).***

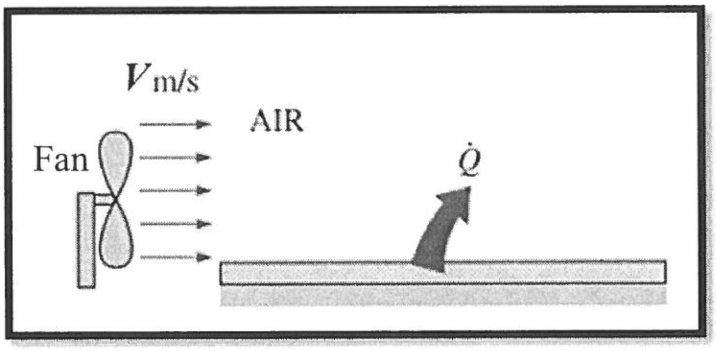


Figure 2(b) / ***Rajah 2(b)***

[4 marks]
[4 *markah*]

(ii) Explain the natural convection with an example.
Jelaskan perolakan semula jadi beserta contoh.

[3 marks]
[3 *markah*]

CLO2 (c) Air at atmospheric pressure and $40^{\circ}C$ flows with a velocity of V = 5m/s over a 2m long flat whose surface is kept at a uniform temperature of $120^{\circ}C$.
Udara pada tekanan atmosfera dan $40^{0}C$ mengalir dengan halaju V = 5m /s di atas flat sepanjang 2 m yang permukaannya disimpan pada suhu seragam $120^{0}C$.

(i) Calculate the film temperature, T_f ($^{\circ}C$), kinematic viscosity, v (m^2/s), Prandtl number, Pr, and Reynold number, Re.
Kirakan *suhu filem, T_f ($^{\circ}C$), kelikatan kinematik, v (m^2 /s), nombor prandtl, Pr, dan nombor Reynold, Re.*

[7 marks]
[7 *markah*]

(ii) Calculate the heat transfer rate between the 2 m plate and the air per 1m width of the plate.
Kirakan kadar pemindahan haba diantara 2 m plat dan udara per 1m lebar plat.

[7 marks]
[7 *markah*]

QUESTION 3
SOALAN 3

CLO1 (a) Blackbody radiation is the thermal electromagnetic radiation within, or surrounding.
Radiasi jasad hitam adalah radiasi elektromagnetik termal dalaman, atau persekitaran.

(i) Explain blackbody.
Terangkan jasad hitam.

[3 marks]
[3 *markah*]

(ii) Explain electromagnetic spectrum.
Terangkan spektrum elektromagnetik.

[3 marks]
[3 *markah*]

CLO2 (b) For a blackbody maintained at 115°C, calculate
Sinaran jasad hitam dikekalkan pada 115°C, kirakan

(i) the total blackbody emissive power.
kuasa pancaran keseluruhan jasad hitam.

[4 marks]
[4 *markah*]

(ii) the wavelength at which the maximum monochromatic emissive power occurs and the maximum monochromatic emissive power.
panjang gelombang di mana daya pancaran monokromatik maksimum berlaku dan kuasa pelepasan monokromatik maksimum.

[7 marks]
[7 *markah*]

CLO2 (c) The glass window with 3 mm thickness has transmitted 95% of the radiation between 0.40 and 3.0 μm and is essentially opaque for radiation at other wavelength. Calculate the rate of radiation transmitted through a 3 m x 3 m glass window from blackbody source at 2000 K.

Tingkap kaca dengan ketebalan 3 mm telah menghantar 95% sinaran antara 0.4 dan 3.0 µm dan pada asasnya legap untuk sinaran pada panjang gelombang lain. Kirakan kadar sinaran yang dihantar melalui tingkap kaca 3 m x 3 m dari sumber jasad hitam pada 2000 K.

[8 marks]

[8 *markah*]

QUESTION 4

SOALAN 4

CLO1 (a) By using appropriate diagram, indicate parallel flow and counter flow in heat exchanger application.

Menggunakan rajah yang sesuai, tunjukkan aliran selari dan aliran berlawanan dalam aplikasi pemindah haba.

[4 marks]

[4 *markah*]

CLO1 (b) Heat exchangers are devices that facilitate the exchange of heat between two fluids that are at different temperatures while keeping them from mixing with each other. There are two types of flow arrangement which are possible in a double-pipe heat exchanger.

Penukar haba ialah peranti yang memudahkan pertukaran haba antara dua cecair yang berada pada suhu yang berbeza disamping menghalang mereka daripada bercampur antara satu sama lain. Terdapat dua jenis susunan aliran yang mungkin dalam penukar haba dua berkembar.

(i) Explain the fluid flow of the heat exchanger shown in **Figure 4(b).**

*Terangkan aliran bendalir bagi pemindah haba dalam **Rajah 4(b).***

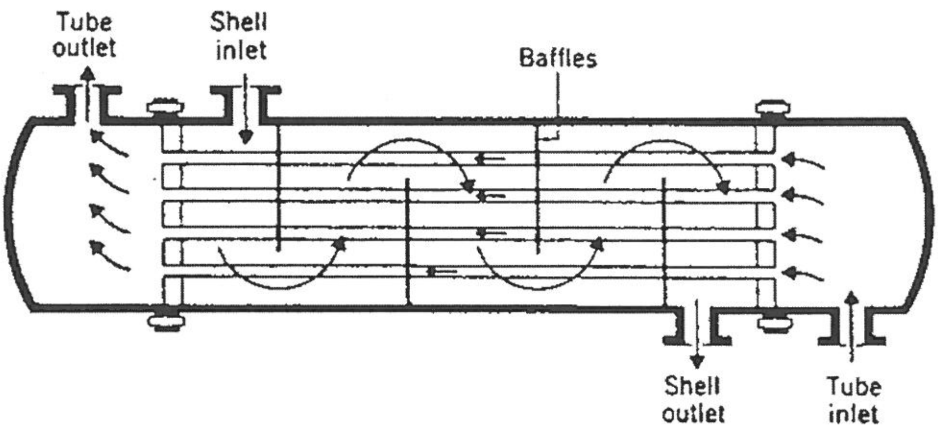


Figure 4(b) / *Rajah 4(b)*

[5 marks]

[5 *markah*]

ii) The performance of heat exchangers usually deteriorates with time as a result of accumulation of deposits on heat transfer surfaces. Explain the thermal resistance due to fouling in a heat exchanger by considering the fluid velocity and temperature cause by the fouling.

Prestasi penukar haba biasanya merosot dengan masa disebabkan oleh pengumpulan mendapan pada permukaan pemindahan haba. Terangkan rintangan haba akibat kekotoran dalam penukar haba yang mengambil kira prestasi halaju bendalir dan suhu yang dipengaruhi kekotoran.

[5 marks]

[5 *markah*]

CLO2 (c) A stream of hot oil (C_p= 2.2 kJ/kg.°C) is cooled at a rate of 0.2 kg/s from temperature 150°C to 40°C in the tube side of a double-pipe counter-flow heat exchanger. Water (C_p=4.18 kJ/ kg.°C) enters the heat exchanger at temperature 10°C with a rate of 0.15 kg/s. The outside diameter of the inner tube is 2.5 cm and its length is 6 m.

Aliran minyak panas (C_p= 2.2 kJ/kg.°C) disejukkan pada kadar 0.2 kg/s daripada suhu 150°C kepada 40°C dibahagian dalam tiub penukar haba ganda dua aliran berlawanan. Air (C_p=4.18 kJ/ kg.°C) memasuki penukar haba pada suhu 10°C dengan kadar 0.15 kg/s. Diameter luar tiub ialah 2.5 cm dan panjang 6 m.

(i) Calculate the heat transfer rate and water outlet temperature.

Kirakan kadar pemindahan haba dan suhu air yang keluar.

[5 marks]

[5 *markah*]

(ii) Calculate the overall heat transfer coefficient for the heat exchanger.

Kirakan pekali pemindahan haba keseluruhan bagi penukar haba.

[6 marks]

[6 *markah*]

SOALAN TAMAT

HEAT TRANSFER FORMULA

Conduction

$$Q_{conduction} = \frac{T_1 - T_2}{R}$$

$$Q_{conduction,plate} = kA\frac{T_1 - T_2}{X}$$

Conduction Resistance (Plane), $R_{wall} = \frac{X}{kA}$

Conduction Resistance (Cylinder), $R_{cyl} = \frac{\ln(^{r2}/_{r1})}{2\pi Lk}$

Conduction Resistance (Sphere), $R_{sphere} = \frac{r2 - r1}{4\pi r_1 r_2 k}$

Thermal Resistance Concept, $Q = \frac{\Delta T}{R_{total}}$

Series Thermal Resistance, $Rtotal = R1 + R2 + R3 + \cdots$

Parallel Thermal Resistance, $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$

Convection

$\dot{Q}_{conv} = hA_s(T_s - T_\infty)$

Convection Resistance, $R_{conv} = \frac{1}{Ah}$

Film, temperature, $T_f = \frac{T_s + T_\infty}{2}$

Nusselt number, $N_{Nu} = \frac{hL}{k} = \frac{hD}{k}$

Reynold Number for plate, $N_{Re} = \frac{\rho vL}{\mu}$

Reynold Number for plate, $N_{Re} = \frac{vL}{v}$

Reynold Number for cylinder/sphere, $N_{Re} = \frac{\rho vD}{\mu}$

Reynold Number for cylinder/sphere, $N_{Re} = \frac{vD}{v}$

Parallel flow over a flat plate

Laminar flow (For Reynold Number, $N_{Re} < 5 \times 10^5$):

$N_{Nu} = 0.664 {N_{Re}}^{0.5} \mathrm{Pr}^{1/3}$

Turbulence flow (For Reynold Number, $5 \times 10^5 \leq N_{Re} \leq 10^7$ and $0.6 \leq \mathrm{Pr} \leq 60$):

$N_{Nu} = 0.037 {N_{Re}}^{0.8} \mathrm{Pr}^{1/3}$

Flow across cylinder

$$N_{Nu} = 0.3 + \frac{0.62 {N_{Re}}^{1/2} \mathrm{Pr}^{1/3}}{[1 + \left(\frac{0.4}{\mathrm{Pr}}\right)^{\frac{2}{3}}]^{1/4}} [1 + (\frac{N_{Re}}{282000})^{\frac{5}{8}}]^{4/5}$$

Note: For ($N_{Re} \times \mathrm{Pr} > 0.2$), Fluid properties at T_f.

Flow across sphere

$$N_{Nu} = 2 + \left[0.4N_{Re}^{\frac{1}{2}} + 0.06N_{Re}^{\frac{2}{3}}\right] Pr^{0.4}\left(\frac{\mu_\infty}{\mu_s}\right)^{1/4}$$

Note: Fluid properties is referring to the surrounding temperature, T_∞ except μ_s is referred to T_s.

Flow across tube banks

$$A_1 = S_T L$$

$$A_T = (S_T - D)L$$

$$A_D = (S_D - D)L$$

In line flow direction:

$$V_{max} = \frac{S_T}{S_T - D}(V)$$

Staggered flow direction:

If $S_D > \frac{(S_T+D)}{2}$:

$$V_{max} = \frac{S_T}{S_T - D}V$$

If $S_D < \frac{(S_T+D)}{2}$:

$$V_{max} = \frac{S_T}{2(S_D - D)}V$$

$$N_{Re} = \frac{\rho V_{max} D}{\mu} = \frac{V_{max} D}{v}$$

$$N_{Nu,new} = F.N_{Nu}$$

$$A_s = N\pi DL$$

$N = N_L \times N_T$

$Q = A_s h \Delta T_{ln}$

Nusselt Number correlation in tube banks:

Arrangement	Range of Re_D	Correlation
In-line	0–100	$Nu_D = 0.9\, Re_D^{0.4} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	100–1000	$Nu_D = 0.52\, Re_D^{0.5} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	$1000–2 \times 10^5$	$Nu_D = 0.27\, Re_D^{0.63} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	$2 \times 10^5–2 \times 10^6$	$Nu_D = 0.033\, Re_D^{0.8} Pr^{0.4} (Pr/Pr_s)^{0.25}$
Staggered	0–500	$Nu_D = 1.04\, Re_D^{0.4} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	500–1000	$Nu_D = 0.71\, Re_D^{0.5} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	$1000–2 \times 10^5$	$Nu_D = 0.35 (S_T/S_L)^{0.2}\, Re_D^{0.6} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	$2 \times 10^5–2 \times 10^6$	$Nu_D = 0.031 (S_T/S_L)^{0.2}\, Re_D^{0.8} Pr^{0.36} (Pr/Pr_s)^{0.25}$

*All properties except Pr_s are to be evaluated at the arithmetic mean of the inlet and outlet temperatures of the fluid (Pr_s is to be evaluated at T_s).

Nusselt number correction factor calculation:

Correction factor F to be used in $Nu_{D,N_L} = F Nu_D$ for $N_L < 16$ and $Re_D > 1000$ (from Zukauskas, Ref 15, 1987).

N_L	1	2	3	4	5	7	10	13
In-line	0.70	0.80	0.86	0.90	0.93	0.96	0.98	0.99
Staggered	0.64	0.76	0.84	0.89	0.93	0.96	0.98	0.99

Internal Flow Convection (Cylinder)

For laminar flow:

$$T_{ave\ bulk} = \frac{T_{bi} + T_{bo}}{2}$$

$$N_{Nu} = 1.86 (N_{Re} N_{Pr} \frac{D}{L})^{\frac{1}{3}} (\frac{\mu_b}{\mu_w})^{0.14}$$

$$\dot{Q}_{conv} = h_a A_s \Delta T_a$$

$$\Delta T_a = \frac{(T_w - T_{bi}) + (T_w - T_{bo})}{2}$$

For turbulent flow:

$$N_{Nu} = 0.027 {N_{Re}}^{0.8} Pr^{\frac{1}{3}} (\frac{\mu_b}{\mu_w})^{0.14}$$

Note: For $N_{Re} > 6000$, $0.7 < Pr < 16000$ and $L/D > 60$

$$\dot{Q}_{conv} = h_L A_s \Delta T_{lm}$$

$$\Delta T_{lm} = \frac{(T_w - T_{bi}) - (T_w - T_{bo})}{\ln(\frac{T_w - T_{bi}}{T_w - T_{bo}})}$$

Radiation

$Q_{rad} = \varepsilon\sigma A_s(T_s{}^4 - T_\infty{}^4)$, $\sigma = 5.670 \times 10\text{-}8\ W/m^2.K^4$

$$E_{b\lambda}(\lambda, T) = \frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T}\right) - 1\right]}\ \ W/m^2.\mu m$$

$C_1 = 3.742 \times 10^8 W.\mu m^4/m^2$

$C_2 = 1.439 \times 10^4 \mu m.K$

Fraction of radiation:

$f_{\lambda 1-\lambda 2}(T) = f_{\lambda 2}(T) - f_{\lambda 1}(T)$

Wien's displacement law:

$\lambda T = 2897.8 \mu m.K$

Heat Exchanger

$$R_{total} = R_i + R_{wall} + R_o = \frac{1}{h_i A_i} + \frac{(^{Do}/_{Di})}{2\pi kL} + \frac{1}{h_o A_o}$$

$$R_{wall} = \frac{(^{Do}/_{Di})}{2\pi kL}$$

$$Q = \frac{\Delta T}{R} = UA\Delta T_{LM} = U_i A_i \Delta T_{LM} = U_o A_o \Delta T_{LM}$$

$$\frac{1}{U_O A_S} = \frac{1}{U_i A_i} = \frac{1}{U_o A_0} = R_{total}$$

$$T_{ave} = \frac{T_{bi} + T_{bo}}{2}$$

$$\frac{1}{U} \approx \frac{1}{h_i} + \frac{1}{h_o}$$

Fouling factor:

$$R_{fouling} = \frac{R_{factor}}{A}$$

Shell flow (Laminar):

D_i / D_o	N_{Nu}
0	0
0.05	17.46
0.1	11.56
0.25	7.37
0.5	5.74
1.0	4.86

Shell flow (Turbulent):

$$N_{Nu} = 0.3 + \frac{0.62 N_{Re}{}^{1/2} Pr^{1/3}}{[1 + \left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}]^{1/4}} [1 + (\frac{N_{Re}}{282000})^{\frac{5}{8}}]^{4/5}$$

Tube flow (Laminar):

$$N_{Nu} = 1.86(N_{Re}N_{Pr}\frac{D}{L})^{\frac{1}{3}}(\frac{\mu_b}{\mu_w})^{0.14}$$

Tube flow (Turbulent):

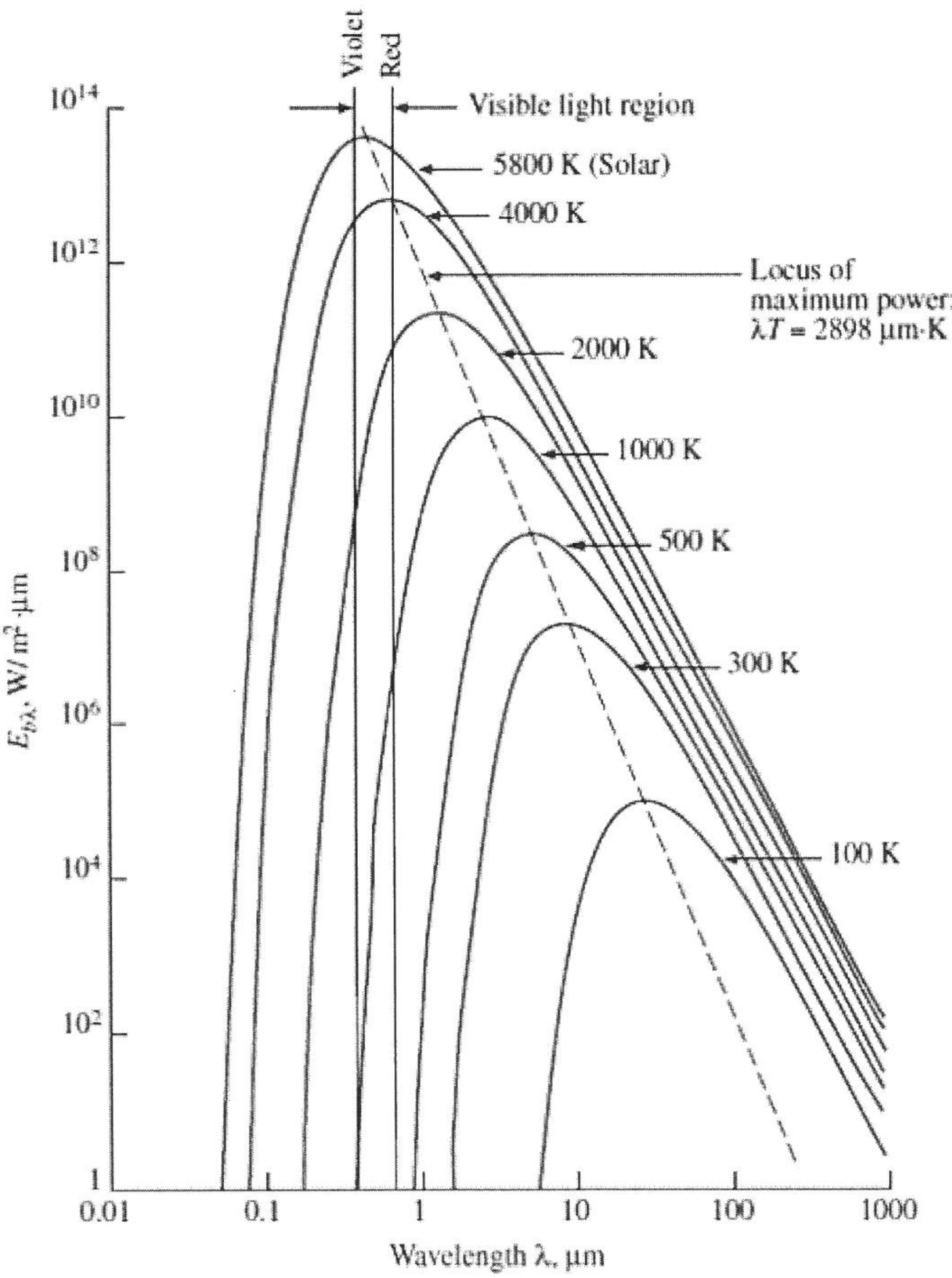
$$Nu = 0.023Re^{0.8}Pr^{0.4}$$

Table of Unit Conversion

Quantity	Equivalent Values
Mass	1 kg = 1000 g = 0.001 metric ton = 2.20462 lb_m = 35.27392 oz 1 lb_m = 16 oz = 5 X 10^{-4} ton = 453.593 g = 0.453593 kg
Length	1 m = 100 cm = 1000 mm = 10^6 microns (μm) = 10^{10} angstroms (A) = 39.37 in. = 3.2808 ft = 1.0936 yd = 0.0006214 mile
Volume	1 m^3 = 1000 liters = 10^6 cm^3 = 10^6 ml = 35.3145 ft^3 = 220.83 imperial gallons = 264.17 gal = 1056.68 qt 1 ft^3 = 1728 in^3 = 7.4805 gal = 0.028317 m^3 = 28.317 liters = 28 317 cm^3
Force	1 N = 1 kg.m/s^2 = 10^5 dynes = 10^5 g.cm/s^2 = 0.22481 lb_f 1 lb_f = 32.174 lbm.ft/s^2 = 4.4482 N = 4.4482 X 10^4 dynes
Pressure	1 atm = 1.01325 x 10^5 N/m^2 (Pa) = 101.325 kPa = 1.01325 bars = 1.01325 x 10^6 dynes/cm^2 = 760 mm Hg at 0 °C (torr) = 10.333 m H_2O at 4 °C = 14.696lb_f/in^2 (psi) = 33.9 ft H_2O at 4 °C = 29.921 in Hg at 0 °C
Energy	1 J = 1 N.m = 10^7 ergs = 10^7 dyne.cm = 2.778 x 10^{-7} kW.h = 0.23901 cal = 0.7376 ft-lb_f = 9.486 x 10^{-4} Btu
Power	1 W = 1J/s = 0.23901 cal/s = 0.7376 ft.lb_f/s = 9.468 x 10^{-4} Btu/s = 1.341 x 10^{-3} hp

Blackbody radiation functions f_λ

λT, μm · K	f_λ	λT, μm · K	f_λ
200	0.000000	6200	0.754140
400	0.000000	6400	0.769234
600	0.000000	6600	0.783199
800	0.000016	6800	0.796129
1000	0.000321	7000	0.808109
1200	0.002134	7200	0.819217
1400	0.007790	7400	0.829527
1600	0.019718	7600	0.839102
1800	0.039341	7800	0.848005
2000	0.066728	8000	0.856288
2200	0.100888	8500	0.874608
2400	0.140256	9000	0.890029
2600	0.183120	9500	0.903085
2800	0.227897	10,000	0.914199
3000	0.273232	10,500	0.923710
3200	0.318102	11,000	0.931890
3400	0.361735	11,500	0.939959
3600	0.403607	12,000	0.945098
3800	0.443382	13,000	0.955139
4000	0.480877	14,000	0.962898
4200	0.516014	15,000	0.969981
4400	0.548796	16,000	0.973814
4600	0.579280	18,000	0.980860
4800	0.607559	20,000	0.985602
5000	0.633747	25,000	0.992215
5200	0.658970	30,000	0.995340
5400	0.680360	40,000	0.997967
5600	0.701046	50,000	0.998953
5800	0.720158	75,000	0.999713
6000	0.737818	100,000	0.999905



Violet
Red
Visible light region
5800 K (Solar)
4000 K
Locus of maximum power: λT = 2898 μm·K
2000 K
1000 K
500 K
300 K
100 K
10^14
10^12
10^10
10^8
10^6
10^4
10^2
1
0.01
0.1
1
10
100
1000
E_bλ, W/ m²·μm
Wavelength λ, μm

TABLE A-13

Properties of liquids

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	Volume Expansion Coeff. β, 1/K
				Methane [CH_4]				
−160	420.2	3492	0.1863	1.270×10^{-7}	1.133×10^{-4}	2.699×10^{-7}	2.126	0.00352
−150	405.0	3580	0.1703	1.174×10^{-7}	9.169×10^{-5}	2.264×10^{-7}	1.927	0.00391
−140	388.8	3700	0.1550	1.077×10^{-7}	7.551×10^{-5}	1.942×10^{-7}	1.803	0.00444
−130	371.1	3875	0.1402	9.749×10^{-8}	6.288×10^{-5}	1.694×10^{-7}	1.738	0.00520
−120	351.4	4146	0.1258	8.634×10^{-8}	5.257×10^{-5}	1.496×10^{-7}	1.732	0.00637
−110	328.8	4611	0.1115	7.356×10^{-8}	4.377×10^{-5}	1.331×10^{-7}	1.810	0.00841
−100	301.0	5578	0.0967	5.761×10^{-8}	3.577×10^{-5}	1.188×10^{-7}	2.063	0.01282
−90	261.7	8902	0.0797	3.423×10^{-8}	2.761×10^{-5}	1.055×10^{-7}	3.082	0.02922
				Methanol [$CH_3(OH)$]				
20	788.4	2515	0.1987	1.002×10^{-7}	5.857×10^{-4}	7.429×10^{-7}	7.414	0.00118
30	779.1	2577	0.1980	9.862×10^{-8}	5.088×10^{-4}	6.531×10^{-7}	6.622	0.00120
40	769.6	2644	0.1972	9.690×10^{-8}	4.460×10^{-4}	5.795×10^{-7}	5.980	0.00123
50	760.1	2718	0.1965	9.509×10^{-8}	3.942×10^{-4}	5.185×10^{-7}	5.453	0.00127
60	750.4	2798	0.1957	9.320×10^{-8}	3.510×10^{-4}	4.677×10^{-7}	5.018	0.00132
70	740.4	2885	0.1950	9.128×10^{-8}	3.146×10^{-4}	4.250×10^{-7}	4.655	0.00137
				Isobutane (R600a)				
−100	683.8	1881	0.1383	1.075×10^{-7}	9.305×10^{-4}	1.360×10^{-6}	12.65	0.00142
−75	659.3	1970	0.1357	1.044×10^{-7}	5.624×10^{-4}	8.531×10^{-7}	8.167	0.00150
−50	634.3	2069	0.1283	9.773×10^{-8}	3.769×10^{-4}	5.942×10^{-7}	6.079	0.00161
−25	608.2	2180	0.1181	8.906×10^{-8}	2.688×10^{-4}	4.420×10^{-7}	4.963	0.00177
0	580.6	2306	0.1068	7.974×10^{-8}	1.993×10^{-4}	3.432×10^{-7}	4.304	0.00199
25	550.7	2455	0.0956	7.069×10^{-8}	1.510×10^{-4}	2.743×10^{-7}	3.880	0.00232
50	517.3	2640	0.0851	6.233×10^{-8}	1.155×10^{-4}	2.233×10^{-7}	3.582	0.00286
75	478.5	2896	0.0757	5.460×10^{-8}	8.785×10^{-5}	1.836×10^{-7}	3.363	0.00385
100	429.6	3361	0.0669	4.634×10^{-8}	6.483×10^{-5}	1.509×10^{-7}	3.256	0.00628
				Glycerin				
0	1276	2262	0.2820	9.773×10^{-8}	10.49	8.219×10^{-3}	84,101	
5	1273	2288	0.2835	9.732×10^{-8}	6.730	5.287×10^{-3}	54,327	
10	1270	2320	0.2846	9.662×10^{-8}	4.241	3.339×10^{-3}	34,561	
15	1267	2354	0.2856	9.576×10^{-8}	2.496	1.970×10^{-3}	20,570	
20	1264	2386	0.2860	9.484×10^{-8}	1.519	1.201×10^{-3}	12,671	
25	1261	2416	0.2860	9.388×10^{-8}	0.9934	7.878×10^{-4}	8,392	
30	1258	2447	0.2860	9.291×10^{-8}	0.6582	5.232×10^{-4}	5,631	
35	1255	2478	0.2860	9.195×10^{-8}	0.4347	3.464×10^{-4}	3,767	
40	1252	2513	0.2863	9.101×10^{-8}	0.3073	2.455×10^{-4}	2,697	
				Engine Oil (unused)				
0	899.0	1797	0.1469	9.097×10^{-8}	3.814	4.242×10^{-3}	46,636	0.00070
20	888.1	1881	0.1450	8.680×10^{-8}	0.8374	9.429×10^{-4}	10,863	0.00070
40	876.0	1964	0.1444	8.391×10^{-8}	0.2177	2.485×10^{-4}	2,962	0.00070
60	863.9	2048	0.1404	7.934×10^{-8}	0.07399	8.565×10^{-5}	1,080	0.00070
80	852.0	2132	0.1380	7.599×10^{-8}	0.03232	3.794×10^{-5}	499.3	0.00070
100	840.0	2220	0.1367	7.330×10^{-8}	0.01718	2.046×10^{-5}	279.1	0.00070
120	828.9	2308	0.1347	7.042×10^{-8}	0.01029	1.241×10^{-5}	176.3	0.00070
140	816.8	2395	0.1330	6.798×10^{-8}	0.006558	8.029×10^{-6}	118.1	0.00070
150	810.3	2441	0.1327	6.708×10^{-8}	0.005344	6.595×10^{-6}	98.31	0.00070

Source: Data generated from the EES software developed by S. A. Klein and F. L. Alvarado. Originally based on various sources.

TABLE A–9

Properties of saturated water

Temp. T, °C	Saturation Pressure P_{sat}, kPa	Density ρ, kg/m^3 Liquid	Density Vapor	Enthalpy of Vaporization h_{fg}, kJ/kg	Specific Heat c_p, J/kg·K Liquid	Specific Heat Vapor	Thermal Conductivity k, W/m·K Liquid	Thermal Conductivity Vapor	Dynamic Viscosity μ, kg/m·s Liquid	Dynamic Viscosity Vapor	Prandtl Number Pr Liquid	Prandtl Number Vapor	Volume Expansion Coefficient β, 1/K Liquid
0.01	0.6113	999.8	0.0048	2501	4217	1854	0.561	0.0171	1.792×10^{-3}	0.922×10^{-5}	13.5	1.00	-0.068×10^{-3}
5	0.8721	999.9	0.0068	2490	4205	1857	0.571	0.0173	1.519×10^{-3}	0.934×10^{-5}	11.2	1.00	0.015×10^{-3}
10	1.2276	999.7	0.0094	2478	4194	1862	0.580	0.0176	1.307×10^{-3}	0.946×10^{-5}	9.45	1.00	0.733×10^{-3}
15	1.7051	999.1	0.0128	2466	4185	1863	0.589	0.0179	1.138×10^{-3}	0.959×10^{-5}	8.09	1.00	0.138×10^{-3}
20	2.339	998.0	0.0173	2454	4182	1867	0.598	0.0182	1.002×10^{-3}	0.973×10^{-5}	7.01	1.00	0.195×10^{-3}
25	3.169	997.0	0.0231	2442	4180	1870	0.607	0.0186	0.891×10^{-3}	0.987×10^{-5}	6.14	1.00	0.247×10^{-3}
30	4.246	996.0	0.0304	2431	4178	1875	0.615	0.0189	0.798×10^{-3}	1.001×10^{-5}	5.42	1.00	0.294×10^{-3}
35	5.628	994.0	0.0397	2419	4178	1880	0.623	0.0192	0.720×10^{-3}	1.016×10^{-5}	4.83	1.00	0.337×10^{-3}
40	7.384	992.1	0.0512	2407	4179	1885	0.631	0.0196	0.653×10^{-3}	1.031×10^{-5}	4.32	1.00	0.377×10^{-3}
45	9.593	990.1	0.0655	2395	4180	1892	0.637	0.0200	0.596×10^{-3}	1.046×10^{-5}	3.91	1.00	0.415×10^{-3}
50	12.35	988.1	0.0831	2383	4181	1900	0.644	0.0204	0.547×10^{-3}	1.062×10^{-5}	3.55	1.00	0.451×10^{-3}
55	15.76	985.2	0.1045	2371	4183	1908	0.649	0.0208	0.504×10^{-3}	1.077×10^{-5}	3.25	1.00	0.484×10^{-3}
60	19.94	983.3	0.1304	2359	4185	1916	0.654	0.0212	0.467×10^{-3}	1.093×10^{-5}	2.99	1.00	0.517×10^{-3}
65	25.03	980.4	0.1614	2346	4187	1926	0.659	0.0216	0.433×10^{-3}	1.110×10^{-5}	2.75	1.00	0.548×10^{-3}
70	31.19	977.5	0.1983	2334	4190	1936	0.663	0.0221	0.404×10^{-3}	1.126×10^{-5}	2.55	1.00	0.578×10^{-3}
75	38.58	974.7	0.2421	2321	4193	1948	0.667	0.0225	0.378×10^{-3}	1.142×10^{-5}	2.38	1.00	0.607×10^{-3}
80	47.39	971.8	0.2935	2309	4197	1962	0.670	0.0230	0.355×10^{-3}	1.159×10^{-5}	2.22	1.00	0.653×10^{-3}
85	57.83	968.1	0.3536	2296	4201	1977	0.673	0.0235	0.333×10^{-3}	1.176×10^{-5}	2.08	1.00	0.670×10^{-3}
90	70.14	965.3	0.4235	2283	4206	1993	0.675	0.0240	0.315×10^{-3}	1.193×10^{-5}	1.96	1.00	0.702×10^{-3}
95	84.55	961.5	0.5045	2270	4212	2010	0.677	0.0246	0.297×10^{-3}	1.210×10^{-5}	1.85	1.00	0.716×10^{-3}
100	101.33	957.9	0.5978	2257	4217	2029	0.679	0.0251	0.282×10^{-3}	1.227×10^{-5}	1.75	1.00	0.750×10^{-3}
110	143.27	950.6	0.8263	2230	4229	2071	0.682	0.0262	0.255×10^{-3}	1.261×10^{-5}	1.58	1.00	0.798×10^{-3}
120	198.53	943.4	1.121	2203	4244	2120	0.683	0.0275	0.232×10^{-3}	1.296×10^{-5}	1.44	1.00	0.858×10^{-3}
130	270.1	934.6	1.496	2174	4263	2177	0.684	0.0288	0.213×10^{-3}	1.330×10^{-5}	1.33	1.01	0.913×10^{-3}
140	361.3	921.7	1.965	2145	4286	2244	0.683	0.0301	0.197×10^{-3}	1.365×10^{-5}	1.24	1.02	0.970×10^{-3}
150	475.8	916.6	2.546	2114	4311	2314	0.682	0.0316	0.183×10^{-3}	1.399×10^{-5}	1.16	1.02	1.025×10^{-3}
160	617.8	907.4	3.256	2083	4340	2420	0.680	0.0331	0.170×10^{-3}	1.434×10^{-5}	1.09	1.05	1.145×10^{-3}
170	791.7	897.7	4.119	2050	4370	2490	0.677	0.0347	0.160×10^{-3}	1.468×10^{-5}	1.03	1.05	1.178×10^{-3}
180	1,002.1	887.3	5.153	2015	4410	2590	0.673	0.0364	0.150×10^{-3}	1.502×10^{-5}	0.983	1.07	1.210×10^{-3}
190	1,254.4	876.4	6.388	1979	4460	2710	0.669	0.0382	0.142×10^{-3}	1.537×10^{-5}	0.947	1.09	1.280×10^{-3}
200	1,553.8	864.3	7.852	1941	4500	2840	0.663	0.0401	0.134×10^{-3}	1.571×10^{-5}	0.910	1.11	1.350×10^{-3}
220	2,318	840.3	11.60	1859	4610	3110	0.650	0.0442	0.122×10^{-3}	1.641×10^{-5}	0.865	1.15	1.520×10^{-3}
240	3,344	813.7	16.73	1767	4760	3520	0.632	0.0487	0.111×10^{-3}	1.712×10^{-5}	0.836	1.24	1.720×10^{-3}
260	4,688	783.7	23.69	1663	4970	4070	0.609	0.0540	0.102×10^{-3}	1.788×10^{-5}	0.832	1.35	2.000×10^{-3}
280	6,412	750.8	33.15	1544	5280	4835	0.581	0.0605	0.094×10^{-3}	1.870×10^{-5}	0.854	1.49	2.380×10^{-3}
300	8,581	713.8	46.15	1405	5750	5980	0.548	0.0695	0.086×10^{-3}	1.965×10^{-5}	0.902	1.69	2.950×10^{-3}
[illegible]0	11,274	667.1	64.57	1239	6540	7900	0.509	0.0836	0.078×10^{-3}	2.084×10^{-5}	1.00	1.97	
340	14,586	610.5	92.62	1028	8240	11,870	0.469	0.110	0.070×10^{-3}	2.255×10^{-5}	1.23	2.43	
360	18,651	528.3	144.0	720	14,690	25,800	0.427	0.178	0.060×10^{-3}	2.571×10^{-5}	2.06	3.73	
374.14	22,090	317.0	317.0	0	—	—	—	—	0.043×10^{-3}	4.313×10^{-5}			

Note 1: Kinematic viscosity ν and thermal diffusivity α can be calculated from their definitions, $\nu = \mu/\rho$ and $\alpha = k/\rho c_p = \nu/\text{Pr}$. The temperatures 0.01°C, 100°C, and 374.14°C are the triple-, boiling-, and critical-point temperatures of water, respectively. The properties listed above (except the vapor density) can be used at any pressure with negligible error except at temperatures near the critical-point value.

Note 2: The unit kJ/kg·°C for specific heat is equivalent to kJ/kg·K, and the unit W/m·°C for thermal conductivity is equivalent to W/m·K.

Source: Viscosity and thermal conductivity data are from J. V. Sengers and J. T. R. Watson, *Journal of Physical and Chemical Reference Data* 15 (1986), pp. 1291–1322. Other data are obtained from various sources or calculated.

TABLE A–15

Properties of air at 1 atm pressure

Temp. T, °C	Density ρ, kg/m^3	Specific Heat c_p, J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m^2/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m^2/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^{-5}	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 c_p, k, μ, and Pr are independent of pressure. The properties ρ, ν, and α at a pressure P (in atm) other than 1 atm are determined by multiplying the values of ρ at the given temperature by P and by dividing ν and α by P.

Source: Data generated from the EES software developed by S. A. Klein and F. L. Alvarado. Original sources: Keenan, Chao, Keyes, Gas Tables, Wiley, 1984; and Thermophysical Properties of Matter. Vol. 3: Thermal Conductivity, Y. S. Touloukian, P. E. Liley, S. C. Saxena, Vol. 11: Viscosity, Y. S. Touloukian, S. C. Saxena, and P. Hestermans, IFI/Plenun, NY, 1970, ISBN 0-306067020-8.