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 I : 2023/2024

DGP30122 : HEAT TRANSFER

TARIKH : 17 DISEMBER 2023
MASA : 8.30 PAGI – 10.30 PAGI (2 JAM)

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

Struktur (4 soalan)

Dokumen sokongan yang disertakan : Formula, Jadual

JANGAN BUKA KERTAS SOALAN INI SEHINGGA DIARAHKAN

(CLO yang tertera hanya sebagai rujukan)

SULIT

INSTRUCTION:
This paper consists of **FOUR (4)** structured questions. Answer **ALL** questions.

ARAHAN:
*Kertas ini mengandungi **EMPAT (4)** soalan berstruktur.Jawab **SEMUA** soalan.*

QUESTION 1
SOALAN 1

(a) Thermodynamics and heat transfer are related fields within the broader subject of thermal science, but they focus on different aspects of energy and heat interactions.
Termodinamik dan pemindahan haba ialah bidang yang berkaitan dalam subjek sains haba yang luas, tetapi fokus kepada perbezaan aspek tenaga dan interaksi haba.

CLO 1 i. List **TWO (2)** mechanisms of heat transfer.
*Senaraikan **DUA (2)** mekanisme pemindahan haba.*

[2 marks]
[*2 markah*]

CLO 1 ii. State the definition of blackbody and real body.
Nyatakan definisi jasad hitam dan jasad sebenar.

[4 marks]
[*4 markah*]

CLO 1 (b) Explain the mechanism of heat transfer by convection with the aid of **Diagram B1** below.
Terangkan mekanisme pemindahan haba dengan konduksi dengan bantuan Rajah B1 dibawah.

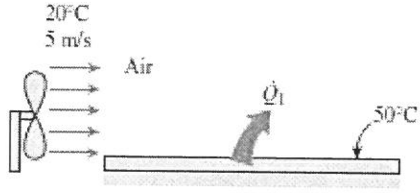


Diagram B1/*Rajah B1*

[4 marks]
[*4 markah*]

(c) A flat plate with a thermal conductivity of 100 W/m °C has a 2 cm thickness. Heat is being applied at point T1 at a surface temperature of 50 °C and surface area of 8 m^2 as shown in Diagram C1.

Satu plat rata dengan kekonduksian haba 100 W/m °C mempunyai ketebalan 2 cm. Haba dikenakan pada titik T1 pada suhu permukaan 50 °C dan luas permukaan 8 m^2 seperti yang ditunjuk dalam Rajah C1.

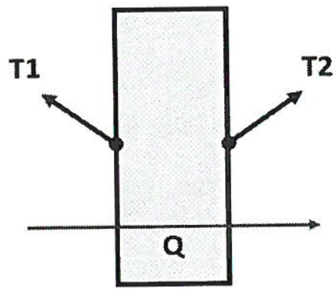


Diagram C1/ *Rajah C1*

CLO 2 i. Calculate the temperature, T2 if the heat transfer is 800 kW.

Kirakan suhu, T2 sekiranya pemindahan haba sebanyak 800 kW.

[7 marks]
[*7 markah*]

CLO 2 ii. The manufacturing material of the plate is changed to aluminium which has a thermal conductivity of 273 W/m.°C. The temperatures T1 and T2 are measured to be 50 °C and 20 °C. If the plate dimension remains the same, calculate the amount that needs to be paid by a person if the energy rate is RM 0.05/ KW. Assume radiation and convective heat transfer are neglected.

Bahan buatan plat tersebut ditukar kepada aluminium yang mempunyai kekonduksian haba sebanya 273 W/m.°C. Suhu T1 dan T2 disukat menjadi 50 °C dan 20 °C. Jika dimensi plat kekal sama, kirakan jumlah yang perlu dibayar oleh seseorang sekiranya kadar tenaga ialah RM 0.05 / KW. Anggap radiasi dan pemindahan haba perolakan diabaikan.

[8 marks]
[*8 markah*]

QUESTION 2
SOALAN 2

CLO 1 (a) Define natural convection and force convection.
Takrifkan perolakan semula jadi dan perolakan paksa.

[4 marks]
[*4 markah*]

(b) A 25 cm diameter stainless steel ball is removed from the oven at a uniform temperature. The ball is then subjected to the flow of air at 1 atm pressure and 25 °C with a velocity of 3 m/s. The surface temperature of the ball eventually drops to 250 °C.
25 cm diameter bola besi tahan karat dikeluarkan dari ketuhar pada suhu yang sekata. Bola tersebut kemudiannya dikenakan udara yang mengalir pada tekanan 1 atm dan 25 °C dengan had laju 3 m/s. Suhu permukaan bola tersebut kemudiannya menurun kepada 250 °C.

CLO 1 i. Report the value of density, thermal conductivity, dynamic viscosity, and Prandtl Number by referring to the surrounding temperature.
Laporkan nilai ketumpatan, kekonduksian haba, kelikatan dinamik dan nombor Prandtl dengan merujuk kepada suhu sekeliling.

[4 marks]
[*4 markah*]

CLO 1 ii. Determine the Reynold Number.
Tentukan Nombor Reynold.

[3 marks]
[*3 markah*]

(c) During the winter season, a 0.1 m diameter of a process line pipe with an external surface temperature is 120 °C passes through one open area that is not protected against the surrounding cold temperature. The wind is blowing across the cylindrical pipe at a velocity of 10 m/s and a temperature of -20 °C (1 atm pressure).
Pada musim sejuk, satu paip laluan proses berdiameter 0.1 m dengan suhu permukaan luar 120 °C melalui satu kawasan terbuka yang tidak dilindungi daripada suhu luar yang sejuk. Angin tersebut bertiup menyeberangi paip silinder itu pada had laju 10 m/s dan suhu -20 °C (1atm tekanan).

CLO 2 i. Calculate the Nusselt Number, N_{Nu} for this case.
Kira Nombor Nusselt, N_{Nu} untuk kes ini.

[7 marks]
[*7 markah*]

CLO 2 ii. Calculate the convective heat transfer rate across that cylinder pipe if the length of the pipe is 20 m.
Kira kadar pemindahan haba secara perolakan menyeberangi paip silinder tersebut sekiranya panjang paip ialah 20m.

[7 marks]
[*7 markah*]

QUESTION 3
SOALAN 3

(a) Radiation properties refer to the characteristics and behaviors of radiation, which is the emission or transmission of energy in the form of waves or particles.
Sifat-sifat radiasi merujuk kepada ciri-ciri dan perilaku radiasi, iaitu pelepasan dan penghantaran tenaga dalam bentuk gelombang atau zarah.

CLO 1 i. Explain the definition of radiation.
Jelaskan definisi radiasi.

[3 marks]
[3 markah]

CLO 1 ii. Explain reflectivity in radiation emission characteristics.
Jelaskan kebolehpantulan dalam ciri-ciri pelepasan radiasi.

[3 marks]
[3 markah]

(b) A cubical object at a surface temperature of 800 K is suspended in the air. Assume the cube closely approximates a blackbody. Each side of the cube has a length of 75 cm.
Objek kiub pada suhu permukaan 800 K terapung di udara. Andaikan kiub tersebut mendekati sebuah badan hitam. Setiap sisi kiub itu mempunyai panjang 75 cm.

CLO 2 i. Calculate the blackbody maximum rate of radiation emitted by the 6 cube surfaces.
Kira kadar maksimum radiasi jasad hitam yang dipancarkan oleh 6 permukaan kiub.

[4 marks]
[4 markah]

CLO 2 ii. At one time, there were 2 types of real bodies with the same dimension as the cubical body. The emissivity value of the bodies is Ɛ1: 0.50 and Ɛ2: 0.8. Calculate the total radiation emitted by the bodies at a surrounding temperature of 350 K.

Pada satu masa, terdapat 2 jenis jasad sebenar dengan dimensi yang sama dengan kiub. Nilai keberpancaran jasad tersebut ialah Ɛ1: 0.50 dan Ɛ2: 0.8. Kirakan jumlah radiasi yang dikeluarkan oleh jasad tersebut pada suhu sekitar 350 K.

[7 marks]

[*7 markah*]

CLO 2 (c) The temperature of an object that approximates a blackbody is 8000 K. Calculate the fraction of radiation emitted by the object in the wavelength of $\lambda 1 = 0.4$ μm to $\lambda 2 = 0.8$ μm.

Suhu sebuah objek yang menghampiri jasad hitam ialah 8000 K. Kira pecahan radiasi yang dikeluarkan objek pada Panjang gelombang $\lambda 1 = 0.4$ μm hingga $\lambda 2 = 0.8$ μm.

[8 marks]

[*8 markah*]

QUESTION 4
SOALAN 4

CLO 1 (a) Heat exchangers are extensively used in the chemical manufacturing industry for processes like heating, cooling, condensing, and evaporating various chemicals. It helps regulate temperatures, control reactions, and recover waste heat. List **FOUR (4)** types of heat exchangers.
Penukar haba digunakan secara meluas dalam industri pembuatan kimia untuk proses seperti pemanasan, pendinginan, kondensasi, dan penguapan pelbagai bahan kimia. Ia membantu mengawal suhu, mengawal tindak balas, dan mengembalikan haba sisa. Senaraikan ***EMPAT (4)*** *jenis penukar haba.*

[4 marks]
[*4 markah*]

(b) A shell and tube heat exchanger is a type of heat exchanger that consists of a shell (outer vessel) and a set of tubes (inner tubes) arranged within the shell.
Penukar haba kelompang dan tiub ialah penukar haba yang mempunyai cengkerang (vessel luar) dan set tiub (tiub dalam) disusun dalam cengkerang.

CLO 1 i. Explain **TWO (2)** properties of shell and tube heat exchangers.
Jelaskan **DUA (2)** ciri-ciri *penukar haba kelompang dan tiub.*

[5 marks]
[*5 markah*]

CLO 1 ii. Explain the fouling phenomenon in heat exchangers.
Terangkan fenomena kekotoran dalam penukar haba.

[5 marks]
[*5 markah*]

(c) A double-pipe counter-flow heat exchanger aims to cool down process flow using cooling water.

Penukar haba paip berganda yang beraliran balas bertujuan untuk menyejukkan aliran proses dengan menggunakan air sejuk.

CLO 2 i. Draw a complete label of the temperature profile diagram for the process.

Lukis dengan label yang lengkap gambarajah profil suhu bagi proses tersebut.

[5 marks]

[*5 markah*]

CLO 2 ii. The internal tube, A_i and h_i are measured to be 10 m^2 and 80 $W/m^2.K$ and the outer tube, A_o and h_o are measured to be 12 m^2 and 60 $W/m^2.K$. Other than that, the wall resistance, R_{wall} is measured to be 0.05 K/W. Calculate the total resistances for the heat exchanger if the fouling is neglected.

Tiub dalam, A_i and h_i disukat pada 10 m^2 dan 80 $W/m^2.K$ dan tiub luar, A_o dan h_o disukat pada 12 m^2 dan 60 $W/m^2.K$. Selain itu, rintangan dinding, R_{wall} disukat pada 0.05 K/W. Kirakan jumlah rintangan keseluruhan bagi penukar haba tersebut sekiranya 'fouling' diabaikan.

[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), $R_{cyl} = \frac{\ln\left({}^{r2}/_{r1}\right)}{2\pi Lk}$

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

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

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

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

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

$$\text{Reynold Number for plate, } N_{Re} = \frac{\rho v L}{\mu}$$

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

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

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

Parallel flow over a flat plate

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

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

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

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

Flow across cylinder

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

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

Flow across sphere

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

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

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

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

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

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

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

$$Q = mC_p\Delta T$$

$$Q_{hot} = Q_{cold}$$

$$R_{total} = R_i + R_{wall} + R_o = \frac{1}{h_i A_i} + \frac{\ln({D_o}/{D_i})}{2\pi kL} + \frac{1}{h_o A_o}$$

$$R_{wall} = \frac{\ln({D_o}/{D_i})}{2\pi kL}$$

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

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

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

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

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):

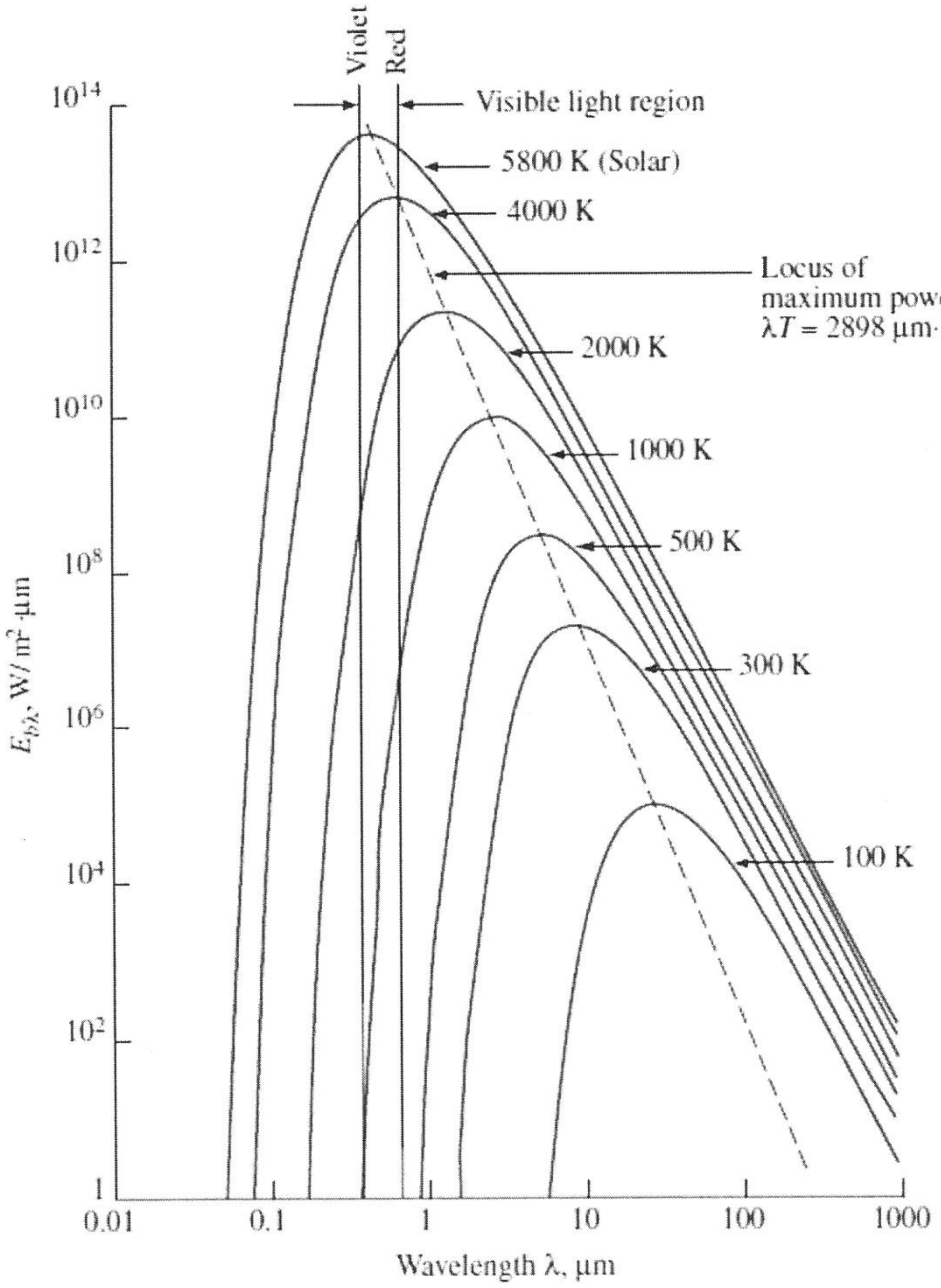
$$Nu = 0.023 Re^{0.8} Pr^{0.4}$$

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, $\mu m \cdot K$	f_λ	λT, $\mu m \cdot K$	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–9

Properties of saturated water

Temp. T, °C	Saturation Pressure P_{sat}, 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
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}
320	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–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–15

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^{-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.