SULIT

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

JABATAN KEJURUTERAAN PETROKIMIA

PEPERIKSAAN AKHIR

SESI II : 2021 / 2022

DGP30122 : HEAT TRANSFER

TARIKH : 3 JULAI 2022
MASA : 8.30 PAGI - 10.30 PAGI (2 JAM)

Kertas ini mengandungi **SEPULUH (10)** halaman bercetak.

Struktur (4 soalan)

Dokumen sokongan yang disertakan : Formula / Lampiran

JANGAN BUKA KERTAS SOALAN INI SEHINGGA DIARAHKAN

(CLO yang tertera hanya sebagai rujukan)

SULIT

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

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

QUESTION 1

SOALAN 1

CLO1 C1

(a) There are three mechanisms of heat transfer.
Terdapat tiga mekanisme pemindahan haba.

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

[2 marks]
[*2 markah*]

(ii) Refer to your answer in 1(a) (i), describe the mechanisms of each heat transfer.
Merujuk kepada jawapan anda dalam 1(a) (i), terangkan mekanisme bagi setiap pemindahan haba.

[4 marks]
[*4 markah*]

CLO1 C2

(b) Express the thermal resistance network for combined series and parallel wall for Figure 1(b).
Gambarkan rangkaian rintangan haba untuk gabungan dinding sesiri dan selari bagi Rajah 1(b).

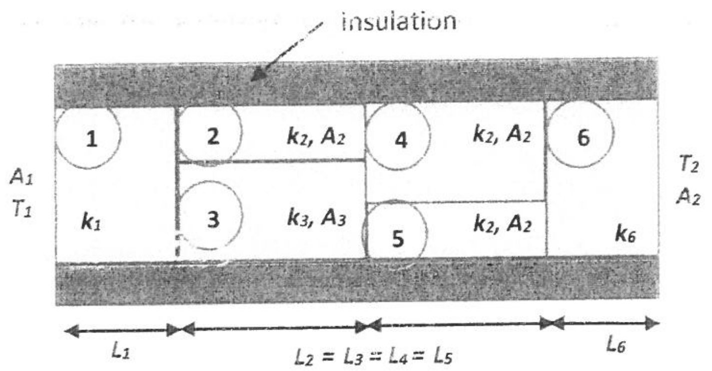

Figure 1(b) / *Rajah 1(b)*

[4 marks]

[4 markah]

CLO2 C3

(c) Consider a 1.2-m-high and 2-m-wide double-pane window consisting of two 3-mm-thick layers of glass (k=0.78 W/m·°C) separated by a 12-mm-wide stagnant air space (k = 0.026 W/m .°C). Take the convection heat transfer coefficients on the inner and outer surfaces of the window to be h_1 =10 W/m^2·°C and h_2 =25 W/m^2·°C, and disregard any heat transfer by radiation. Calculate

Pertimbangkan 1.2-m tinggi dan 2-m lebar tingkap dua panel yang terdiri daripada 3-mm ketebalan kaca (k=0.78 W/m · °C) dan dpisahkan oleh 12-mm lebar ruang udara tidak bergerak (k=0.026 W/m·°C). Diberi pekali pemindahan haba perolakan untuk permukaan dalam dan permukaan luar tingkap ialah h_1 =10 W/m^2·°C and h_2 =25 W/m^2·°C. Abaikan sebarang pemindahan haba radiasi. Kirakan

(i) the thermal resistance of the window against heat conduction.

rintangan haba bagi tingkap tersebut terhadap pengaliran haba.

[7 marks]

[7 markah]

(ii) the temperature of its inner surface for a day during which the room is maintained at 24°C while the temperature of the outdoors is -5°C.
suhu pada permukaan dalam sepanjang hari di mana suhu bilik kekal pada 24°C dan suhu persekitaraan luar pada -5°C.

[8 marks]
[*8 markah*]

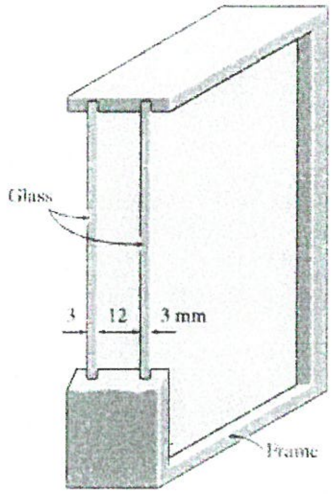

Figure 1(c) / *Rajah 1(c)*

QUESTION 2
SOALAN 2

CLO1 C1

(a) Describe the laminar and turbulent flows.
Huraikan aliran laminar dan bergelora.

[4 marks]
[*4 markah*]

CLO2 C2

(b) Consider a hot roasted chicken just removed from one oven.
Pertimbangkan seekor ayam panggang yang baru sahaja dikeluarkan daripada sebuah ketuhar.

(i) Explain whether the roasted chicken will cool down faster when the warm air coming from the lungs is blown on it compared with letting it cool naturally at the room temperature.
Terangkan sama ada ayam panggang tersebut akan menyejuk lebih cepat apabila ditiup udara hangat yang datang daripada paru-paru berbanding membiarkannya menyejuk secara semulajadi pada suhu bilik.

[4 marks]
[*4markah*]

(ii) Explain the relation between forced convection and heat transfer rate.
Terangkan hubungan antara perolakan paksa dengan kadar pemindahan haba.

[3 marks]
[*3 markah*]

CLO2 C3

(c) Mercury at 25 °C flows over a 3 m long and 2 m wide flat plate maintained at 50 °C with a velocity of 0.8 m/s.
Merkuri pada suhu 25 °C mengalir di atas plat yang panjang 3 m dan lebar 2 m dikekalkan pada suhu 50 °C dengan halaju 0.8 m/s.

(i) Calculate the total drag force.
Kirakan jumlah daya seret.

[7 marks]
[*7 markah*]

(ii) Calculate the rate of heat transfer over the entire plate per unit width.
Kirakan kadar pemindahan haba di atas keseluruhan plat per unit lebar.

[7 marks]
[*7 markah*]

QUESTION 3

SOALAN 3

CLO1 C2

(a) Radiation is emitted from all directions over a range of wavelength.
Radiasi datang dari pelbagai arah dalam julat gelombang.

(i) Explain how does radiation affects the world life.
Terangkan bagaimana radiasi memberi kesan kepada kehidupan dunia.

[3 marks]
[3 markah]

(ii) Interpret the absorption, reflection, and transmission of incident radiation by a semi-transparent material using an appropriately labelled diagram.
Tafsirkan mengenai penyerapan, bayangan dan pengaliran untuk radiasi tuju oleh bahan separa tembus menggunakan gambarajah yang bersesuaian berserta label yang lengkap .

[3 marks]
[3 markah]

CLO2 C3

(b) Consider a 20cm x 20cm x 20cm cubical body at 1000 K suspended in the air. Assuming the body closely approximates a blackbody, determine
Pertimbangkan sebuah jasad segi empat sama berukuran 20cm x 20cm x 20cm tergantung di udara. Dengan menganggap jasad tersebut adalah jasad hitam, tentukan

(i) the rate at which the cube emits radiation energy, in unit W.
kadar dimana kiub mengeluarkan tenaga radiasi dalam unit W.

[4 marks]
[4 markah]

(ii) the spectral blackbody emissive power at a wavelength of 4 μm.

kuasa pancaran spektrum jasad hitam pada panjang gelombang 4 μm.

[7 marks]

[7 markah]

CLO2
C3

(c) The sun can be treated as a blackbody at an effective surface temperature of 5778K. Compute the fraction of radiation and emissive power at which infrared radiation energy (λ = 0.76 μm – 100 μm) is emitted by the sun.

Matahari dianggap sebagai jasad hitam pada suhu 5778K. Kirakan pecahan radiasi dan kuasa pancaran di mana tenaga radiasi inframerah (λ = 0.76 μm – 100 μm) dipancarkan oleh matahari.

[8 marks]

[8 markah]

QUESTION 4
SOALAN 4

CLO1
C1

(a) Heat exchangers are devices that facilitate the exchange of heat between two fluids that are of different temperatures. State **FOUR (4)** types of heat exchangers.
*Penukar haba adalah peranti yang berfungsi untuk penukaran haba antara dua cecair yang mempunyai suhu berlainan. Nyatakan **EMPAT (4)** jenis penukar haba.*

[4 marks]
[4 markah]

CLO2
C2

(b) A heat exchanger is a system used to transfer heat between two or more fluid. Heat exchangers are classified according to the flow type as parallel flow, counter flow and cross flow arrangement.
Penukar haba diklasifikasikan mengikut jenis aliran iaitu aliran selari, aliran bertentang dan aliran bersilang.

(i) Explain how heat is transferred in a heat exchanger.
Terangkan bagaimana haba dipindahkan dalam penukar haba.

[4 marks]
[4 markah]

(ii) Explain the characteristics of each type of flow.
Terangkan ciri-ciri untuk setiap jenis aliran tersebut.

[6 marks]
[6 markah]

CLO2
C3

(c) The following data relates to a parallel flow heat exchanger in which air is heated by hot exhaust gases. Neglect the tube resistance. Calculate

Data berikut berkaitan dengan penukar haba aliran selari di mana udara dipanaskan oleh gas ekzos panas. Abaikan rintangan tiub. Hitungkan

Table 4(c) / *Jadual 4(c)*

Heat transferred per hour *Pemindahan haba per jam*	200000 kJ
Overall heat transfer coefficient *Pekali pemindahan haba keseluruhan*	70 $W/m^2.^{\circ}C$
Inlet and outlet temperatures of the hot fluid *Suhu masuk dan keluar bendalir panas*	400°C and 200°C *400°C dan 200°C*
Inlet and outlet temperatures of the cold fluid *Suhu masuk dan keluar bendalir sejuk*	50°C and 100°C *50°C dan 100°C*
Inside and outside diameters of the tube *Diameter dalam dan luar tiub*	45mm and 55mm *45mm dan 55mm*

(i) the logarithmic mean temperature difference (LMTD).
bezaaan suhu min logaritma.

[5 marks]
[*5 markah*]

(ii) the length of the tube required for heat transfer to occur.
panjang tiub yang diperlukan untuk pemindahan haba berlaku.

[6 marks]
[*6 markah*]

SOALAN TAMAT

HEAT TRANSFER FORMULA

Conduction

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

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

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

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

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

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

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

Convection

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

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

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

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

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

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

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

Reynold Number in cylinder/sphere, $N_{Re} = \frac{vD}{\nu}$

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, $5 \times 10^5 \leq N_{Re} \leq 10^7$ and $0.6 \leq Pr \leq 60$):

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

Flow across cylinder

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

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

Flow across sphere

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

Note: Fluid properties is refer 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 $S_D < \frac{(S_T+D)}{2}$:

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

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

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

$$A_s = N\pi DL$$

$$N = N_L \times N_T$$

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

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:

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

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

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

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

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

$Q_{rad} = \varepsilon\sigma A_s(T_s^4 - T_{surr}^4)$, $\sigma = 5.670 \times 10^{-8}$ W/m².K⁴

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

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

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

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

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

$$R_{wall} = \frac{(D_o/D_i)}{2\pi k L}$$

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

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

Fouling factor:

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

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

TABLE A-9

Properties of saturated water

Temp. T, °C	Saturation Pressure P_{sat}, kPa	Density ρ, kg/m³ Liquid	Density ρ, kg/m³ Vapor	Enthalpy of Vaporization h_{fg}, kJ/kg	Specific Heat c_p, J/kg·K Liquid	Specific Heat c_p, J/kg·K Vapor	Thermal Conductivity k, W/m·K Liquid	Thermal Conductivity k, W/m·K Vapor	Dynamic Viscosity μ, kg/m·s Liquid	Dynamic Viscosity μ, kg/m·s Vapor	Prandtl Number Pr Liquid	Prandtl Number Pr 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/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.