
UNIVERSITI SAINS MALAYSIA

Second Semester Examination
2014/2015 Academic Session

June 2015

EKC 216 – Process Heat Transfer
[Pemindahan Haba Proses]

Duration : 3 hours
[Masa : 3 jam]

Please ensure that this examination paper contains FIVE printed pages and SEVEN printed pages of Appendix before you begin the examination.

[Sila pastikan bahawa kertas peperiksaan ini mengandungi LIMA muka surat yang bercetak dan TUJUH muka surat Lampiran sebelum anda memulakan peperiksaan ini.]

Instruction: Answer **ALL** questions.

Arahan: Jawab **SEMUA** soalan.]

In the event of any discrepancies, the English version shall be used.

[Sekiranya terdapat sebarang percanggahan pada soalan peperiksaan, versi Bahasa Inggeris hendaklah diguna pakai].

Answer ALL questions.

1. [a] A composite wall is formed as shown in Figure Q.1.[a]. The inside temperature is 420°C and outside air temperature is 30°C . The inside and outside convection coefficients are 12.5 and $34.2 \text{ W/m}^2\cdot\text{K}$, respectively. Assume one-dimensional heat flow, calculate the :

- [i] Temperature at the interface between material B and C.
 [ii] Overall heat transfer coefficient.

[12 marks]

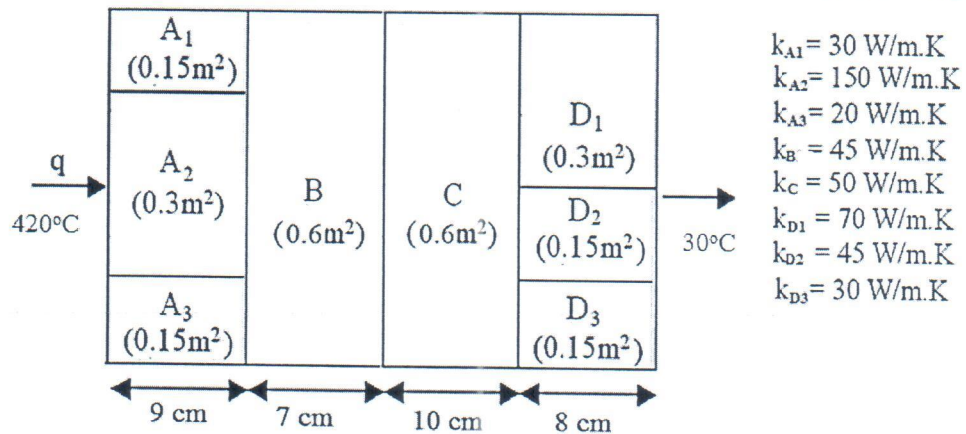


Figure Q.1.[a].

- [b] A superinsulation sphere tank ($k = 3.8 \times 10^{-4} \text{ W/m}\cdot\text{K}$) contains liquid nitrogen at -196°C having an inner and outer diameter of 0.7 m and 0.76 m , respectively. The outer temperature is 26°C . 162 kJ is required to vaporize each kilogram mass of nitrogen at this temperature. Determine the amount of nitrogen vaporized per day.

[4 marks]

- [c] Draw and compare the temperature distributions of pin fin with 0.22 m long and 1.6 cm diameter and exposed to an environment ($h = 9.4 \text{ W/m}^2\cdot\text{K}$) at 25°C , for two fin materials; (a) copper ($k = 385 \text{ W/m}\cdot\text{K}$) and (b) stainless steel ($k = 15 \text{ W/m}\cdot\text{K}$). The base temperature is maintained at 250°C . Assume adiabatic tip condition.

[9 marks]

2. [a] A tube bank consists of a square array of 144 tubes arranged in an in-line array. The tubes have a diameter of 1.5 cm and a length of 2.0 m . The center to center tube spacing is 3.0 cm . If the surface temperature of the tubes is maintained at 500 K and air enters the tube bank at 1 atm , 300 K , and velocity 10 m/s , calculate the total heat lost by the tubes.

[12 marks]

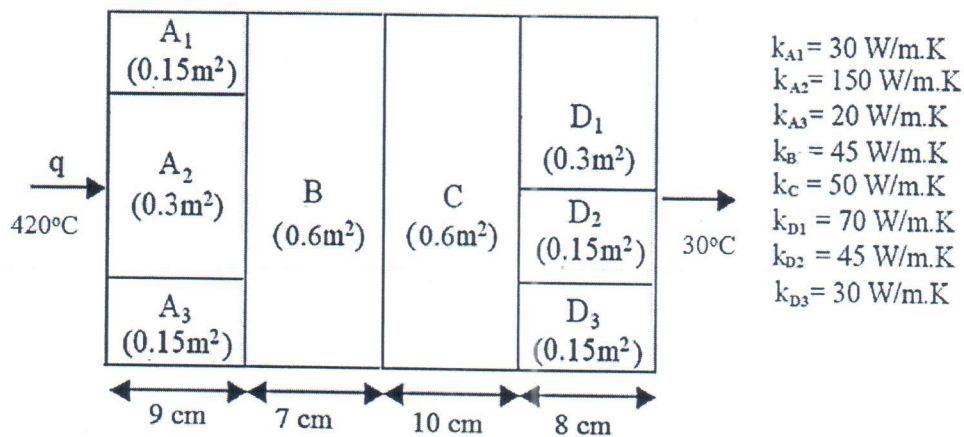
Jawab SEMUA soalan.

1. [a] Sebuah dinding komposit seperti yang ditunjukkan di dalam Rajah S.1.[a] mempunyai suhu di sebelah dalam 420°C dan di bahagian luar 30°C . Pekali perolakan di sebelah dalam dan luar adalah masing-masing 12.5 dan $34.2 \text{ W/m}^2\cdot\text{K}$. Anggap aliran haba berdimensi satu, kirakan:

[i] Suhu antara muka bahan B dan C.

[ii] Pekali keseluruhan pemindahan haba.

[12 markah]



Rajah S.1.[a]

- [b] Suatu tangki sfera dibina dengan bahan penebat lampau ($k = 3.8 \times 10^{-4} \text{ W/m.K}$) berdiameter dalam dan luar masing-masing 0.7 m dan 0.76 m serta mengandungi cecair nitrogen bersuhu -196°C . Suhu luar tangki adalah 26°C . Sebanyak 162 kJ diperlukan untuk menyewap setiap 1 kg nitrogen pada suhu ini. Kirakan jumlah pengewapan nitrogen yang berlaku setiap hari.

[4 markah]

- [c] Lukis dan buat perbandingan taburan suhu bagi sirip pin berdimensi 0.22 m panjang dan 1.6 cm diameter serta terdedah pada persekitaran ($h = 9.4 \text{ W/m}^2\cdot\text{K}$) bersuhu 25°C , untuk 2 jenis bahan sirip; (a) tembaga [$k = 385 \text{ W/m.K}$] dan (b) keluli tahan karat [$k = 15 \text{ W/m.K}$]. Suhu tapak dikekalkan pada 250°C . Anggap keadaan hujung sirip berkeadaan adiabatik.

[9 markah]

2. [a] Barisan 144 tiub disusun dengan tatasusunan segiempat sama. Tiub-tiub tersebut mempunyai diameter 1.5 cm dan panjang 2.0 m . Jarak pusat-ke-pusat tiub ialah 3.0 cm . Jika suhu permukaan tiub dikekalkan pada 500 K dan udara memasuki barisan tiub pada 1 atm , 300 K dan halaju 10 m/s , kirakan jumlah kehilangan haba keseluruhan dari tiub-tiub tersebut.

[12 markah]

- [b] A horizontal fine wire having a diameter of 0.1 mm is maintained at a temperature of 390 K by an electric current. The wire is exposed to air at 1 atm and 310 K. Calculate the electric power necessary to maintain the wire temperature if the length is 5 m.
[6 marks]
- [c] Two vertical plates 75 by 75 cm are separated by a space of 4 cm that is filled with air. Temperature for below and upper plates are 460 K and 340 K, respectively. Calculate the heat transfer across the space.
[7 marks]
3. A saturated steam at 100 psia is to be used to heat carbon dioxide in a crossflow heat exchanger consisting of four hundred brass tubes with an outside diameter of 1/4 inch arranged in a square in-line array. The distance between tube centers is 3/8 inch, in both the normal- and parallel-flow directions. The carbon dioxide flows across the tube bank, while the steam is condensed on the inside of the tubes. A flow rate of 1 lb_m/s of CO₂ at 15 psia and 70°F is to be heated to 200°F. Given that $Nu = 0.254Re^{0.632}$ and heat capacity of carbon dioxide is 0.208 Btu/hr.ft².°F.
- [a] Estimate the length of the tubes to accomplish this heating. Assume that the steam-side heat-transfer coefficient is 1000 Btu/hr.ft².°F and neglect the thermal resistance of the tube wall.
[12 marks]
- [b] Repeat the problem above with the CO₂ flowing on the inside of the tubes and the steam condensing on the outside of the tubes.
[9 marks]
- [c] Compare these two designs [a] and [b] on the basis of CO₂ pressure drop through the exchanger.
[4 marks]
4. A man is enclosed by a small room maintained at an air temperature of 20°C, with convection heat transfer coefficient of $h=8$ W/m².°C. The room walls are at 0°C.
- [a] Calculate the energy lost by the man by combined convection and radiation if his body surface temperature is 25°C.
[10 marks]
- [b] Repeat for a wall temperature of 20°C.
[10 marks]
- [c] Suppose the wall is coated with a highly reflective material. How would that influence the calculation? Alternately, suppose the man's clothing is coated with a reflective material. How would that affect the calculation?
[5 marks]

Note. Be sure to state all assumptions clearly.

- [b] Satu wayar halus mendatar mempunyai diameter 0.1 mm dikekalkan suhu pada 390 K oleh arus elektrik. Wayar tersebut terdedah pada udara 1 atm dan 310 K. Kirakan kuasa elektrik yang diperlukan untuk mengekalkan suhu wayar tersebut untuk panjang wayar 5.0 m. [6 markah]
- [c] Dua plat menegak segiempat sama $75 \text{ cm} \times 75 \text{ cm}$ dipisahkan oleh ruang yang diisi dengan udara sejauh 4 cm. Suhu plat bawah dan atas ialah masing-masing pada 460 K dan 340 K. Kirakan pemindahan haba sepanjang ruang tersebut. [7 markah]
3. Stim tertepu pada 100 psia digunakan untuk memanaskan karbon dioksida di dalam sebuah penukar haba aliran silang yang mempunyai empat ratus tiub-tiub tembaga dengan diameter luar 1/4 inci dengan tatasusunan dalam aturan sejajar segi-empat sama. Jarak antara pusat-pusat tiub ialah 3/8 inci, bagi kedua-dua aliran biasa dan selari. Karbon dioksida mengalir melalui tiub manakala stim tersejat di dalam tiub-tiub tersebut. Satu kadar aliran lb_m/s CO_2 pada 15 psia dan 70°F perlu dipanaskan kepada 200°F . Diberi $\text{Nu} = 0.254\text{Re}^{0.632}$ dan muatan haba karbon dioksida ialah $0.208 \text{ Btu}/\text{j}\cdot\text{ft}^2\cdot^\circ\text{F}$.
- [a] Tentukan panjang tiub-tiub tersebut untuk melengkapkan pemanasan tersebut. Andaikan pemalar penukar haba bahagian-stim ialah $1000 \text{ Btu}/\text{j}\cdot\text{ft}^2\cdot^\circ\text{F}$ dan abaikan rintangan penghabaan dinding tiub tersebut. [12 markah]
- [b] Ulang permasalahan di atas dengan CO_2 mengalir dalam tiub-tiub tersebut dan stim menyejat pada luaran tiub-tiub itu. [9 markah]
- [c] Bandingkan rekabentuk [a] dan [b] ini pada asas tekanan jatuh CO_2 melalui penukar haba ini. [4 markah]
4. Seorang lelaki berada dalam sebuah bilik kecil yang tertutup yang mana suhu udaranya dikekalkan pada 20°C dengan pemalar pemindahan haba olakan $h=8 \text{ W}/\text{m}^2\cdot^\circ\text{C}$. Suhu dinding berada pada 0°C .
- [a] Kirakan tenaga yang hilang oleh lelaki tersebut melalui kombinasi olakan dan radiasi sekiranya suhu permukaan badan heliau ialah 25°C . [10 markah]
- [b] Ulang soalan di atas dengan suhu dinding pada 20°C . [10 markah]
- [c] Andaikan dinding tersebut dilapisi dengan bahan reflektif yang kuat. Bagaimana itu boleh mempengaruhi perkiraan anda? Sebaliknya, andaikan pemakaian lelaki tersebut dilapiskan dengan bahan reflektif. Bagaimana ia mempengaruhi perkiraan anda? [5 markah]
- Nota: Pastikan semua andaian disebut dengan jelas.

Appendix

Common Engineering Conversion Factors

Length	Volume
1 ft = 12 in = 0.3048 m, 1 yard = 3 ft 1 mi = 5280 ft = 1609.344 m 1 nautical mile (nmi) = 6076 ft	1 ft ³ = 0.028317 m ³ = 7.481 gal , 1 bbl = 42 U.S. gal 1 U.S. gal = 231 in ³ = 3.7853 L = 4qt = 0.833 Imp.gal. 1 L = 0.001 m ³ = 0.035315 ft ³ = 0.2642 U.S. gal
Mass	Density
1 slug = 32.174 lb _m = 14.594 kg 1 lb _m = 0.4536 kg = 7000 grains	1 slug/ft ³ = 515.38 kg/m ³ , 1 g/cm ³ = 1000 kg/m ³ 1 lb _m /ft ³ = 16.0185 kg/m ³ , 1 lb _m /in ³ = 27.68 g/cm ³
Acceleration & Area	Velocity
1 ft/s ² = 0.3048 m/s ² 1 ft ² = 0.092903 m ²	1 ft/s = 0.3048 m/s , 1 knot = 1 min/h = 1.6878 ft/s 1 min/h = 1.4666666 ft/s (fps) = 0.44704 m/s
Mass Flow & Mass Flux	Volume Flow
1 slug/s = 14.594 kg/s. 1 lb _m /s = 0.4536 kg/s 1 kg/m ² s = 0.2046 lb _m /ft ² s = 0.00636 slug/ft ² s	1 gal/min = 0.00228 ft ³ /s = 0.06309 L/s 1 million gal/day = 1.5472 ft ³ /s = 0.04381 m ³ /s
Pressure	Force and Surface Tension
1 lb _f /ft ² = 47.88 Pa, 1 torr = 1 mm Hg 1 psi = 144 psf, 1 bar = 10 ⁵ Pa 1 atm = 2116.2 psf = 14.696 psia = 101,325 Pa = 29.9 in Hg = 33.9 ft H ₂ O 1 psia = 6.89476 x 10 ⁴ g/(cm.s ²) = 6.89476 x 10 ³ Pa	1 lb _f = 4.448222 N = 16 oz, 1 dyne = 1 g cm/s ² = 10 ⁻⁵ N 1 kg _f = 2.2046 lb _f = 9.80665 N 1 U.S. (short) ton = 2000 lb _f , 1 N = 0.2248 lb _f 1 N/m = 0.0685 lb _f /ft
Power	Energy and Specific Energy
1 hp = 550 (ft.lb _f)/s = 745.7 W 1 (ft.lb _f)/s = 1.3558 W 1 Watt = 3.4123 Btu/h = 0.00134 hp	1 ft lb _f = 1.35582 J, 1 hp·h = 2544.5 Btu 1 Btu = 252 cal = 1055.056 J = 778.17 ft lb _f 1 cal = 4.1855 J, 1 ft.lb _f /lb _m = 2.9890 J/kg
Specific Weight	Heat Flux
1 lb _f /ft ³ = 157.09 N/m ³	1 W/m ² = 0.3171 Btu/(h ft ²)
Viscosity	Kinematic Viscosity
1 slug/(ft.s) = 47.88 kg/(m.s) = 478.8 poise (p) 1 p = 1 g/(cm.s) 0.1 kg/(m.s) = 0.002088 slug/(ft.s)	1 ft ² /h = 2.506 .10 ⁻⁵ m ² /s, 1 ft ² /s = 0.092903 m ² /s 1 stoke (st) = 1 cm ² /s = 0.0001 m ² /s = 0.001076 ft ² /s
Temperature Scale Readings	
°F = (9/5)°C + 32	°C = (5/9) (°F - 32)
°R = °F + 459.69	°K = °C + 273.16
Thermal Conductivity*	Gas Constant*
1 cal/(s.cm.°C) = 242 Btu/(h.ft.°R) 1 Btu/(h.ft.°R) = 1.7307 W/(m.K)	R = 82.057 atm.cm ³ /(gmol.K) = 62.361 mm Hg.L/(gmol.K) = 1.134 atm.ft ³ /(lbmol.K) = 0.083144 bar.L/(gmol.K) = 10.73 psi. ft ³ /(lbmol. °R) = 555.0 mm Hg.ft ³ /(lbmol. °R)
<p>• Note that the intervals in absolute (Kelvin) and °C are equal. Also, 1 °R = 1 °F. Latent heat: 1 J/kg = 4.2995 × 10⁻⁴ Btu/lb_m = 10.76 lb_f.ft/slug = 0.3345 lb_f.ft/lb_m , 1 Btu/lb_m = 2325.9 J/kg Heat transfer coefficient: 1 Btu/(h.ft².°F) = 5.6782 W/(m².°C). Heat generation rate: 1 W/m³ = 0.09665 Btu/(h ft³) Heat transfer per unit length: 1 W/m = 1.0403 Btu/(h ft) Mass transfer coefficient: 1 m/s = 11.811 ft/h, 1 lb_{mol}/(h.ft²) = 0.013562 kgmol/(s.m²)</p>	

Useful Equations.

$$q_{conduction} = kA \frac{(T_1 - T_2)}{\Delta x}; \quad q_{convection} = hA(T_w - T_\infty); \quad U = \frac{1}{A \sum R}; \quad q_{sphere} = \frac{T_i - T_o}{\frac{1}{(4\pi k)} \left(\frac{1}{r_i} - \frac{1}{r_o} \right)}$$

Fin with adiabatic tip: $\frac{T_x - T_\infty}{T_b - T_\infty} = \frac{\cosh m(L - x)}{\cosh mL}; m^2 = \frac{hP}{kA_c}$

Air flow across tube bank: $Re = \frac{\rho u_{max} d}{\mu} = \frac{\rho v d}{\mu}; u_{max} = u_\infty \frac{S_n}{S_n - d}; Nu = C(Re)^n Pr^{1/3}$

$h = Nu \frac{k}{d}; q = hA(T_w - T_\infty) = \dot{m}_{\infty 1} c_p (T_{\infty 2} - T_{\infty 1}); \dot{m}_{\infty 1} = \rho_{\infty 1} u_{\infty 1} (\text{tube bank height} \times L)$

Free convection: $Gr Pr = \left(\frac{g\beta(T_w - T_\infty)d^3}{\nu^2} \right) Pr; Nu = C(Gr Pr)^m; h = Nu \frac{k}{d}$

Enclosed space: $Gr Pr = \left(\frac{g\beta(T_1 - T_2)\delta^3}{\nu^2} \right) Pr; k_e = kC(Gr Pr)^n \left(\frac{L}{\delta} \right)^m; q = \frac{k_e A(T_1 - T_2)}{\delta}$

Properties of air at atmospheric pressure

The values of $\mu, k, c_p,$ 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 · K	$\mu \times 10^5,$ kg/m · s	$\nu \times 10^6,$ m ² /s	$k,$ W/m · K	$\alpha \times 10^4,$ m ² /s	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

Table 6-4 | Modified correlation of Grimson for heat transfer in tube banks of 10 rows or more, from Reference 12, for use with Equation (6-17).

$\frac{S_p}{d}$	$\frac{S_n}{d}$							
	1.25		1.5		2.0		3.0	
	C	n	C	n	C	n	C	n
In line								
1.25	0.386	0.592	0.305	0.608	0.111	0.704	0.0703	0.752
1.5	0.407	0.586	0.278	0.620	0.112	0.702	0.0753	0.744
2.0	0.464	0.570	0.332	0.602	0.254	0.632	0.220	0.648
3.0	0.322	0.601	0.396	0.584	0.415	0.581	0.317	0.608

TABLE 7-1
Constants for use with Eq. (7-25) for isothermal surfaces

Geometry	$Gr_f Pr_f$	C	m
Vertical planes and cylinders	$10^{-1}-10^4$	Use Fig. 7-7	Use Fig. 7-7
	10^4-10^9	0.59	$\frac{1}{4}$
	10^9-10^{13}	0.021	$\frac{2}{5}$
	10^9-10^{13}	0.10	$\frac{1}{3}$
Horizontal cylinders	$0-10^{-5}$	0.4	0
	$10^{-5}-10^4$	Use Fig. 7-8	Use Fig. 7-8
	10^4-10^9	0.53	$\frac{1}{4}$
	10^9-10^{12}	0.13	$\frac{1}{3}$
	$10^{-10}-10^{-2}$	0.675	0.058
	$10^{-2}-10^2$	1.02	0.148
	10^2-10^4	0.850	0.188
	10^4-10^7	0.480	$\frac{1}{4}$
	10^7-10^{12}	0.125	$\frac{1}{3}$

TABLE 7-3 Summary of empirical relations for free convection in enclosures

Fluid	Geometry	$Gr_s Pr$	Pr	$\frac{L}{\delta}$	C	n	m
Gas	Vertical plate, isothermal	< 2000	$k_c/k = 1.0$	—	—	—	—
		6000-200,000	0.5-2	11-42	0.197	$\frac{1}{4}$	$-\frac{1}{9}$
		200,000- 1.1×10^7	0.5-2	11-42	0.073	$\frac{1}{3}$	$-\frac{1}{9}$
	Horizontal plate, isothermal heated from below	< 1700	$k_c/k = 1.0$	—	—	—	—
		1700-7000	0.5-2	—	0.059	0.4	0
		7000- 3.2×10^5	0.5-2	—	0.212	$\frac{1}{4}$	0
	$> 3.2 \times 10^5$	0.5-2	—	0.061	$\frac{1}{3}$	0	

Useful conversion factors

Physical quantity	Symbol	SI to English conversion	English to SI conversion
Length	L	1 m = 3.2808 ft	1 ft = 0.3048 m
Area	A	1 m ² = 10.7639 ft ²	1 ft ² = 0.092903 m ²
Volume	V	1 m ³ = 35.3134 ft ³	1 ft ³ = 0.028317 m ³
Velocity	v	1 m/s = 3.2808 ft/s	1 ft/s = 0.3048 m/s
Density	ρ	1 kg/m ³ = 0.06243 lb _m /ft ³	1 lb _m /ft ³ = 16.018 kg/m ³
Force	F	1 N = 0.2248 lb _f	1 lb _f = 4.4482 N
Mass	m	1 kg = 2.20462 lb _m	1 lb _m = 0.45359237 kg
Pressure	p	1 N/m ² = 1.45038 × 10 ⁻⁴ lb _f /in ²	1 lb _f /in ² = 6894.76 N/m ²
Energy, heat	q	1 kJ = 0.94783 Btu	1 Btu = 1.05504 kJ
Heat flow	q	1 W = 3.4121 Btu/h	1 Btu/h = 0.29307 W
Heat flux per unit area	q/A	1 W/m ² = 0.317 Btu/h · ft ²	1 Btu/h · ft ² = 3.154 W/m ²
Heat flux per unit length	q/L	1 W/m = 1.0403 Btu/h · ft	1 Btu/h · ft = 0.9613 W/m
Heat generation per unit volume	\dot{q}	1 W/m ³ = 0.096623 Btu/h · ft ³	1 Btu/h · ft ³ = 10.35 W/m ³
Energy per unit mass	q/m	1 kJ/kg = 0.4299 Btu/lb _m	1 Btu/lb _m = 2.326 kJ/kg
Specific heat	c	1 kJ/kg · °C = 0.23884 Btu/lb _m · °F	1 Btu/lb _m · °F = 4.1869 kJ/kg · °C
Thermal conductivity	k	1 W/m · °C = 0.5778 Btu/h · ft · °F	1 Btu/h · ft · °F = 1.7307 W/m · °C
Convection heat-transfer coefficient	h	1 W/m ² · °C = 0.1761 Btu/h · ft ² · °F	1 Btu/h · ft ² · °F = 5.6782 W/m ² · °C
Dynamic Viscosity	μ	1 kg/m · s = 0.672 lb _m /ft · s = 2419.2 lb _m /ft · h	1 lb _m /ft · s = 1.4881 kg/m · s
Kinematic viscosity and thermal diffusivity	ν, α	1 m ² /s = 10.7639 ft ² /s	1 ft ² /s = 0.092903 m ² /s

Important physical constants

Avogadro's number	$N_0 = 6.022045 \times 10^{26}$ molecules/kg mol
Universal gas constant	$R = 1545.35$ ft · lbf/lb _m · mol · °R = 8314.41 J/kg mol · K = 1.986 Btu/lb _m · mol · °R = 1.986 kcal/kg mol · K Planck's constant
Boltzmann's constant	$k = 1.380662 \times 10^{-23}$ J/molecule · K = 8.6173 × 10 ⁻⁵ eV/molecule · K
Speed of light in vacuum	$c = 2.997925 \times 10^8$ m/s
Standard gravitational acceleration	$g = 32.174$ ft/s ² = 9.80665 m/s ²
Electron mass	$m_e = 9.1095 \times 10^{-31}$ kg
Charge on the electron	$e = 1.602189 \times 10^{-19}$ C
Stefan-Boltzmann constant	$\sigma = 0.1714 \times 10^{-8}$ Btu/hr · ft ² · R ⁴ = 5.669 × 10 ⁻⁸ W/m ² · K ⁴
1 atm	= 14.69595 lb _f /in ² = 760 mmHg at 32°F = 29.92 inHg at 32°F = 2116.21 lb _f /ft ² = 1.01325 × 10 ⁵ N/m ²

Figure A1. Effectiveness for 1-2 parallel counter-flow exchanger performance.

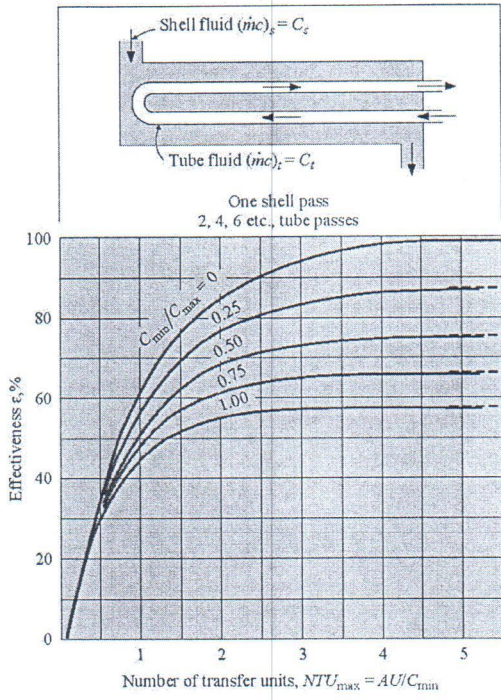


Figure A2. Effectiveness for 2-4 multipass counter-flow exchanger performance.

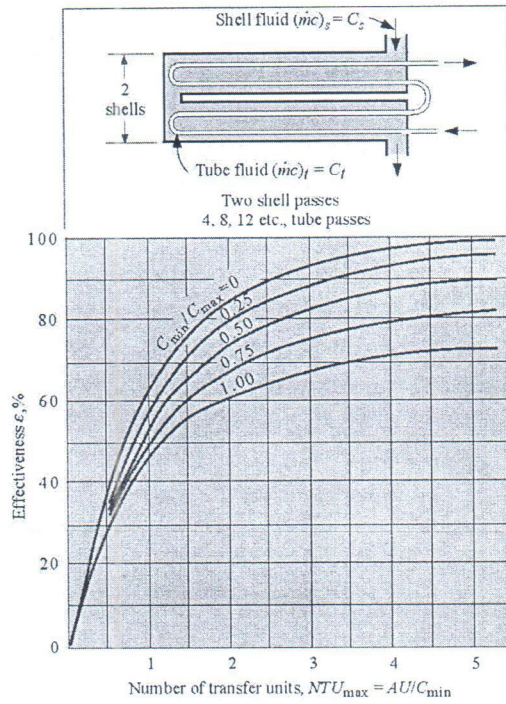


Table A1. Heat-exchanger effectiveness relations

$N = NTU = \frac{UA}{C_{\min}}$ $C = \frac{C_{\min}}{C_{\max}}$	
Flow geometry	Relation
Double pipe:	
Parallel flow	$\epsilon = \frac{1 - \exp[-N(1 + C)]}{1 + C}$
Counterflow	$\epsilon = \frac{1 - \exp[-N(1 - C)]}{1 - C \exp[-N(1 - C)]}$
Counterflow, $C = 1$	$\epsilon = \frac{N}{N + 1}$
Cross flow:	
Both fluids unmixed	$\epsilon = 1 - \exp\left[\frac{\exp(-NCn) - 1}{Cn}\right]$ where $n = N^{-0.22}$
Both fluids mixed	$\epsilon = \left[\frac{1}{1 - \exp(-N)} + \frac{C}{1 - \exp(-NC)} - \frac{1}{N} \right]^{-1}$
C_{\max} mixed, C_{\min} unmixed	$\epsilon = (1/C)[1 - \exp\{-C(1 - e^{-N})\}]$
C_{\max} unmixed, C_{\min} mixed	$\epsilon = 1 - \exp\{-(1/C)[1 - \exp(-NC)]\}$
Shell and tube:	
One shell pass, 2, 4, 6, tube passes	$\epsilon = 2 \left\{ 1 + C + (1 + C^2)^{1/2} \times \frac{1 + \exp[-N(1 + C^2)^{1/2}]}{1 - \exp[-N(1 + C^2)^{1/2}]} \right\}^{-1}$
Multiple shell passes, $2n, 4n, 6n$ tube passes (ϵ_p = effectiveness of each shell pass, n = number of shell passes)	$\epsilon = \frac{[(1 - \epsilon_p C)/(1 - \epsilon_p)]^n - 1}{[(1 - \epsilon_p C)/(1 - \epsilon_p)]^n - C}$
Special case for $C = 1$	$\epsilon = \frac{n\epsilon_p}{1 + (n - 1)\epsilon_p}$
All exchangers with $C = 0$	$\epsilon = 1 - e^{-N}$

Table A2. NTU relations for heat exchangers

$C = C_{\min} / C_{\max}$	$\epsilon = \text{effectiveness}$	$N = \text{NTU} = UA / C_{\min}$
Flow geometry	Relation	
Double pipe:		
Parallel flow		$N = \frac{-\ln[1 - (1 + C)\epsilon]}{1 + C}$
Counterflow		$N = \frac{1}{C - 1} \ln \left(\frac{\epsilon - 1}{C\epsilon - 1} \right)$
Counterflow, $C = 1$		$N = \frac{\epsilon}{1 - \epsilon}$
Cross flow:		
C_{\max} mixed, C_{\min} unmixed		$N = -\ln \left[1 + \frac{1}{C} \ln(1 - C\epsilon) \right]$
C_{\max} unmixed, C_{\min} mixed		$N = \frac{-1}{C} \ln[1 + C \ln(1 - \epsilon)]$
Shell and tube:		
One shell pass, 2, 4, 6, tube passes		$N = -(1 + C^2)^{-1/2} \times \ln \left[\frac{2/\epsilon - 1 - C - (1 + C^2)^{1/2}}{2/\epsilon - 1 - C + (1 + C^2)^{1/2}} \right]$
All exchangers, $C = 0$		$N = -\ln(1 - \epsilon)$