TECHNICAL UNIVERSITY OF MOMBASA

Faculty of Engineering & Technology

DEPARTMENT OF MECHANICAL & AUTOMOTIVE ENGINEERING

UNIVERSITY EXAMINATIONS

FOR THE DEGREE OF BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

EMG 2502 HEAT TRANSFER

SUPPLEMENTARY/SPECIAL EXAMINATIONS

SERIES: SEPTEMBER, 2018

TIME: 2 HOURS

INSTRUCTIONS TO CANDIDATES:

This paper contains **FIVE** questions. Answer **ANY THREE** questions

Supplied: *Thermophysical and Transport Properties of Fluids (SI Edition),* by Y.R. Mayhew and G.F.C. Rogers

The Stefan-Boltzmann constant: $\sigma = 56{\cdot}7 \times 10^{-12}$ kW/m^2 K^4

Question 1

(a) A cylindrical conductor of radius *r*, which is at uniform temperature, is covered with insulation of thermal conductivity *k*. The heat transfer coefficient between the surface of insulation and the surrounding air is *h*. What is the outside radius of the insulation for the heat transfer from the conductor to be a maximum for the given conductor and air temperatures? **(10 marks)**

(b) Steam at a temperature of 250^{o}C flows through a steel pipe of 60-mm inside diameter and 75-mm outside diameter. The convection coefficient between the steam and the inner surface of the pipe is 500 W/m^2·K, while that between the outer surface of the pipe and the surroundings is 25 W/m^2·K. The pipe emissivity is 0.8, and the temperature of the air and the surroundings is 20^{o}C.

(i) Sketch the equivalent thermal circuit of the system,

(ii) Calculate the heat loss per unit length of the pipe. **(10 marks)**

Question 2

(a) A rectangular fin of width W, length L, and thermal conductivity k is exposed to an ambient fluid at temperature T_∞ and having a heat transfer coefficient h. The fin base is maintained at temperature T_o, and the heat loss from the fin tip can be considered negligible compared with that from the lateral surface of the fin.

(i) Starting with the general fin equation $\frac{d^2\theta_{(x)}}{dx^2} - m^2\theta_{(x)} = \mathbf{0}$ develop an expression for temperature distribution $T_{(x)}$ in the fin.

(ii) Develop an expression for the heat transfer rate through the fin.

(12 marks)

(b) An aluminium cylindrical rod ($k = 228{\cdot}4$ W/(m·°C) having diameter of 1·0 cm and length of 10·0 cm is attached to a surface having a temperature of 93·3 °C. The rod is exposed to ambient air at 21·1°C, and the heat transfer coefficient along the length and at the end is 8·52 W/(m^2·°C). **(8 marks)**

Question 3

(a) Define the term '*log mean temperature difference*' (LMTD) as applied to heat exchangers and show that for a counter flow heat exchanger, it is given by:

$$\Delta T_m = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)}$$

where, ΔT_m is the LMTD, ΔT_1 is the temperature difference between the two fluids at one end of the heat exchanger, and ΔT_2 is the temperature difference at the other end. State the assumptions you make. **(10 marks)**

(b) A concentric tube heat exchanger for cooling lubricating oil is comprised of a thin-walled inner tube of 25-mm diameter carrying water and an outer tube of 45-mm diameter carrying the oil. The exchanger operates in counter-flow with an overall heat transfer coefficient of 60 W/m^2 K and the tabulated average properties.

Properties	**Water**	**Oil**
ρ (kg/m^3)	1000	800
c_p (J/kg K)	4200	1900
v (m^2/s)	7×10^{-7}	1×10^{-5}
k (W/m K)	0.64	0.134
Pr	4.7	140

(i) If the outlet temperature of the oil is 60°C, calculate the total heat transfer and the outlet temperature of water.

(ii) Calculate the length of tube required for the heat exchanger.

(10 marks)

Question 4

(a) Starting with the integral boundary layer equation for laminar flow over flat plate in the form:

$$\rho \frac{d}{dx}\int_0^{\delta}(u_\infty - u)u\,dy = \tau_w = \mu \frac{\partial u}{\partial y}\bigg]_{y=0}$$

And using a cubic velocity profile distribution; $\dfrac{u}{u_\infty} = \left[\dfrac{3}{2}\dfrac{y}{\delta} - \dfrac{1}{2}\left(\dfrac{y}{\delta}\right)^3\right]$

obtain an expression for the boundary-layer thickness, expressing your result in terms of the local Reynolds number. **(12 marks)**

(b) Air at 30°C flows over a flat plate at a velocity of 2 m/s. The plate is 2 m long and 1.5 m wide. Assuming a cubic parabola velocity profile distribution, calculate:

(i) The thermal boundary layer thickness at the trailing edge of the plate.

(ii) The total mass flow rate through the boundary between $x = 40$ cm and $x = 85$ cm.

(8 marks)

Question 5

(a) The spectral transmissivity of a glass cover used in a solar collector is given as:

$$\tau_1 = 0 \quad for \quad \lambda \; < \; 0.3\,\mu m$$

$$\tau_2 = 0.9 \quad for \quad \lambda \; < \; 0.3 \quad \lambda \; < \; 3\,\mu m$$

$$\tau_3 = 0 \quad for \quad \lambda \; > \; 3\,\mu m$$

Solar radiation is incident at a rate of 950 W/m^2 and the absorber plate is maintained at 340 K by the cooling water. Determine,

(i) The solar flux incident on the absorber plate,

(ii) The transmissivity of the glass cover for radiation emitted by the absorber plate, and

(iii) The rate of heat transfer to the cooling water if the glass cover temperature is also 340 K. **(10 marks)**

(b) Show that the net radiant heat-transfer rate between two grey surfaces is given by the following expression:

$$Q_{1-2} = \frac{A_1\,\sigma\,(T_1^4 - T_2^4)}{\dfrac{1-\varepsilon_1}{A_1\varepsilon_1} + \dfrac{1}{A_1 F_{1-2}} + \dfrac{1-\varepsilon_2}{A_2\varepsilon_2}}$$

where the symbols have the usual meaning.

Further, show how $Q_{1\text{-}2}$ can be represented as an electrical network. **(10 marks)**

Table A-5 | Properties of air at atmospheric pressure.†

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

T,K	ρ kg/m^3	c_p kJ/kg · °C	$\mu \times 10^5$ kg/m· s	$\nu \times 10^6$ m^2/s	k W/m · °C	$\alpha \times 10^4$ 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
550	0.6423	1.0392	2.848	44.34	0.04360	0.6532	0.680
600	0.5879	1.0551	3.018	51.34	0.04659	0.7512	0.680
650	0.5430	1.0635	3.177	58.51	0.04953	0.8578	0.682
700	0.5030	1.0752	3.332	66.25	0.05230	0.9672	0.684
750	0.4709	1.0856	3.481	73.91	0.05509	1.0774	0.686
800	0.4405	1.0978	3.625	82.29	0.05779	1.1951	0.689
850	0.4149	1.1095	3.765	90.75	0.06028	1.3097	0.692
900	0.3925	1.1212	3.899	99.3	0.06279	1.4271	0.696
950	0.3716	1.1321	4.023	108.2	0.06525	1.5510	0.699
1000	0.3524	1.1417	4.152	117.8	0.06752	1.6779	0.702
1100	0.3204	1.160	4.44	138.6	0.0732	1.969	0.704
1200	0.2947	1.179	4.69	159.1	0.0782	2.251	0.707
1300	0.2707	1.197	4.93	182.1	0.0837	2.583	0.705
1400	0.2515	1.214	5.17	205.5	0.0891	2.920	0.705
1500	0.2355	1.230	5.40	229.1	0.0946	3.262	0.705
1600	0.2211	1.248	5.63	254.5	0.100	3.609	0.705
1700	0.2082	1.267	5.85	280.5	0.105	3.977	0.705
1800	0.1970	1.287	6.07	308.1	0.111	4.379	0.704
1900	0.1858	1.309	6.29	338.5	0.117	4.811	0.704
2000	0.1762	1.338	6.50	369.0	0.124	5.260	0.702
2100	0.1682	1.372	6.72	399.6	0.131	5.715	0.700
2200	0.1602	1.419	6.93	432.6	0.139	6.120	0.707
2300	0.1538	1.482	7.14	464.0	0.149	6.540	0.710
2400	0.1458	1.574	7.35	504.0	0.161	7.020	0.718
2500	0.1394	1.688	7.57	543.5	0.175	7.441	0.730

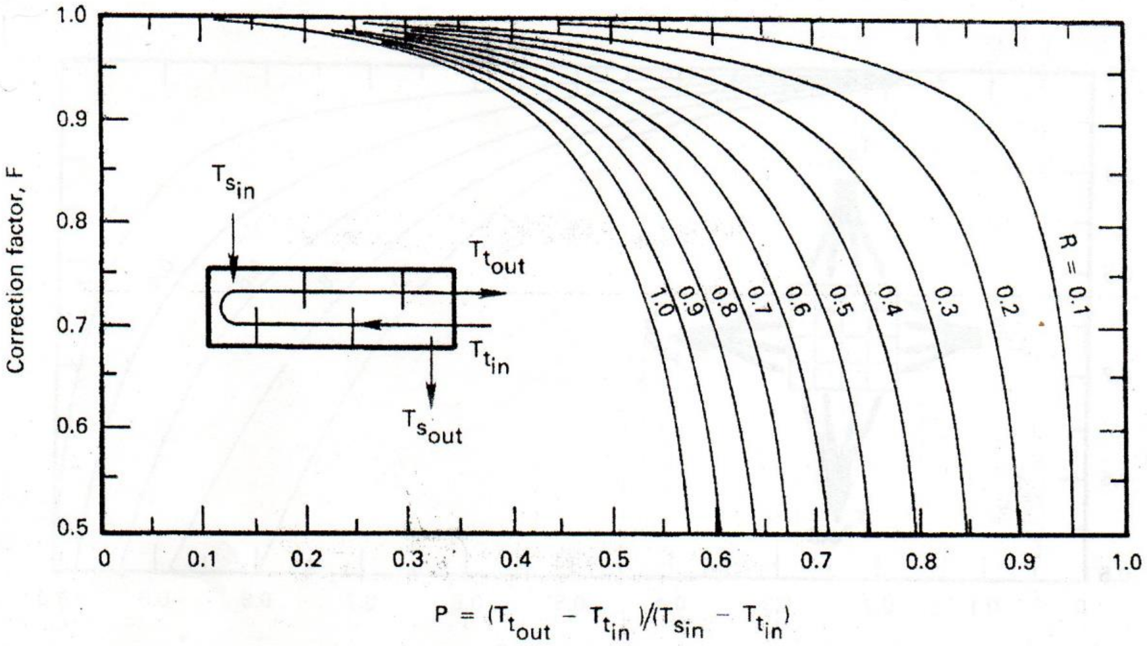
† From *Natl. Bur. Stand. (U.S.) Circ.* 564, 1955.

Table A-6 | Properties of gases at atmospheric pressure[†] (*Continued*).

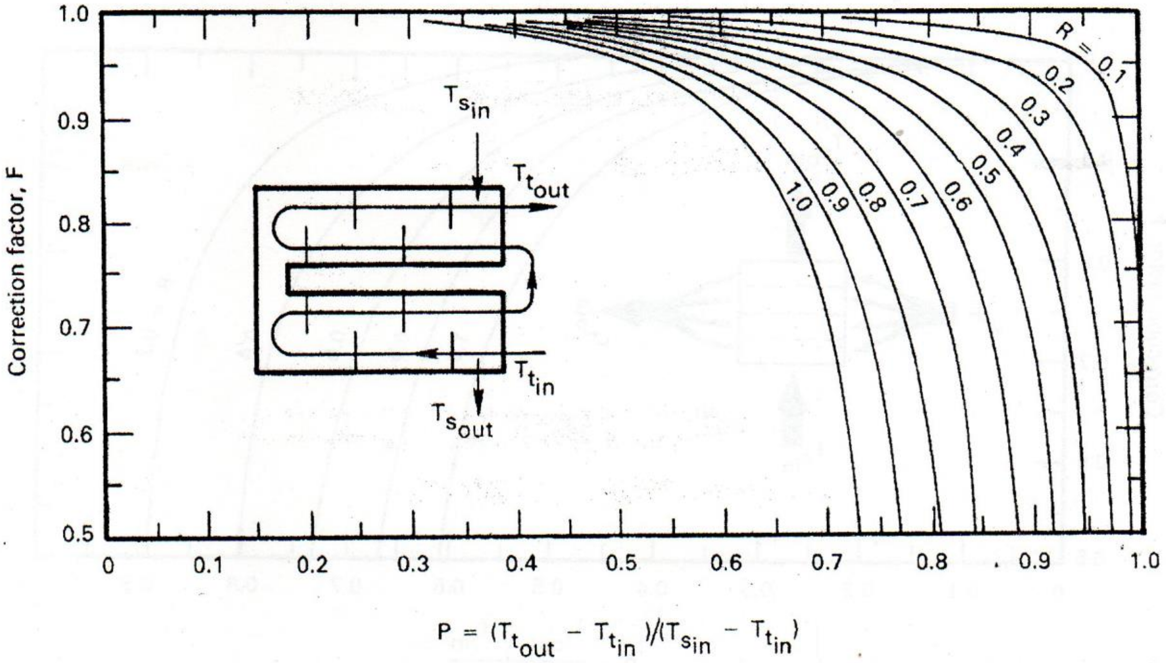
Values of μ, k, c_p, and Pr are not strongly pressure-dependent for He, H_2, O_2, and N_2 and may be used over a fairly wide range of pressures

T, K	ρ kg/m^3	c_p kJ/kg · °C	μ, kg/m · s	ν, m^2/s	k W/m · °C	α, m^2/s	Pr
Carbon dioxide							
220	2.4733	0.783	11.105×10^{-6}	4.490×10^{-6}	0.010805	0.05920×10^{-4}	0.818
250	2.1657	0.804	12.590	5.813	0.012884	0.07401	0.793
300	1.7973	0.871	14.958	8.321	0.016572	0.10588	0.770
350	1.5362	0.900	17.205	11.19	0.02047	0.14808	0.755
400	1.3424	0.942	19.32	14.39	0.02461	0.19463	0.738
450	1.1918	0.980	21.34	17.90	0.02897	0.24813	0.721
500	1.0732	1.013	23.26	21.67	0.03352	0.3084	0.702
550	0.9739	1.047	25.08	25.74	0.03821	0.3750	0.685
600	0.8938	1.076	26.83	30.02	0.04311	0.4483	0.668
Ammonia, NH_3							
273	0.7929	2.177	9.353×10^{-6}	1.18×10^{-5}	0.0220	0.1308×10^{-4}	0.90
323	0.6487	2.177	11.035	1.70	0.0270	0.1920	0.88
373	0.5590	2.236	12.886	2.30	0.0327	0.2619	0.87
423	0.4934	2.315	14.672	2.97	0.0391	0.3432	0.87
473	0.4405	2.395	16.49	3.74	0.0467	0.4421	0.84
Water vapor							
380	0.5863	2.060	12.71×10^{-6}	2.16×10^{-5}	0.0246	0.2036×10^{-4}	1.060
400	0.5542	2.014	13.44	2.42	0.0261	0.2338	1.040
450	0.4902	1.980	15.25	3.11	0.0299	0.307	1.010
500	0.4405	1.985	17.04	3.86	0.0339	0.387	0.996
550	0.4005	1.997	18.84	4.70	0.0379	0.475	0.991
600	0.3652	2.026	20.67	5.66	0.0422	0.573	0.986
650	0.3380	2.056	22.47	6.64	0.0464	0.666	0.995
700	0.3140	2.085	24.26	7.72	0.0505	0.772	1.000
750	0.2931	2.119	26.04	8.88	0.0549	0.883	1.005
800	0.2739	2.152	27.86	10.20	0.0592	1.001	1.010
850	0.2579	2.186	29.69	11.52	0.0637	1.130	1.019

[†] Adapted to SI units from E. R. G. Eckert and R. M. Drake, *Heat and Mass Transfer,* 2nd ed. New York: McGraw-Hill, 1959.

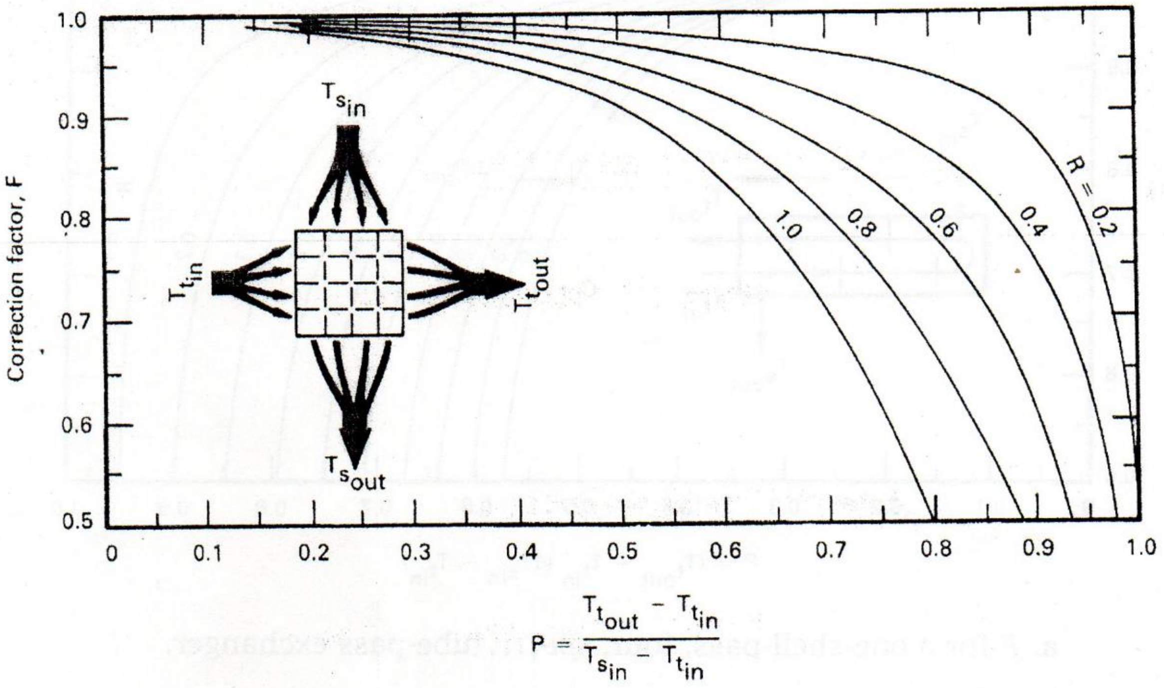


a. *F* for a one-shell-pass, four, six-,... tube-pass exchanger.

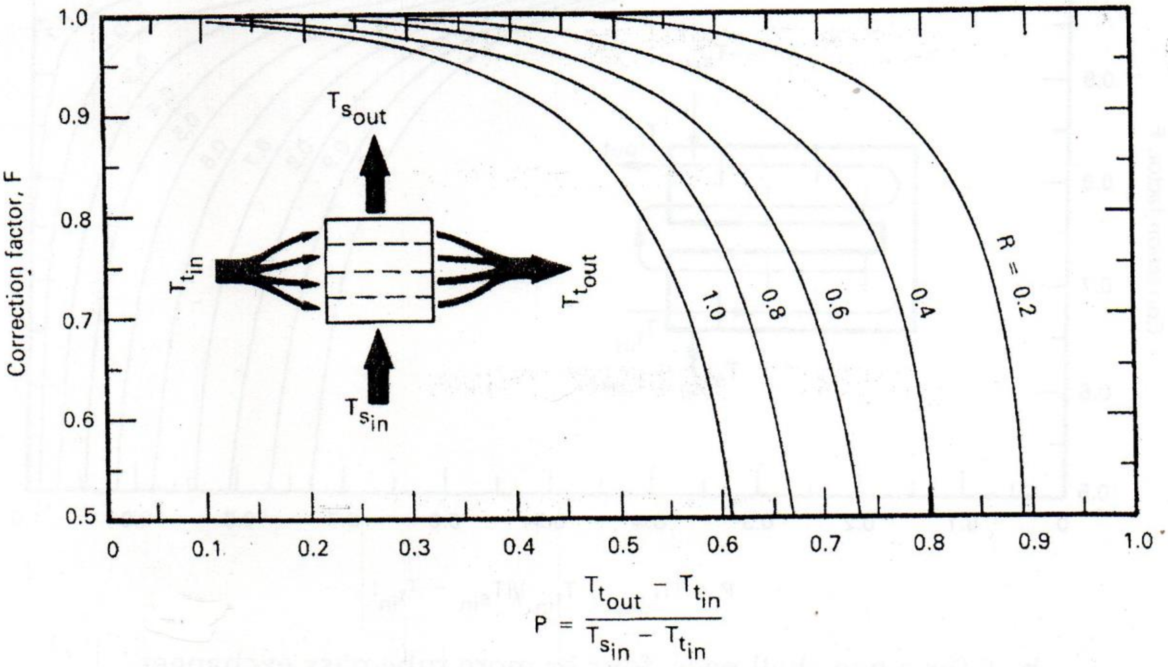


b. *F* for a two-shell-pass, four or more tube-pass exchanger.

Figure LMTD correction factors, *F*, for multipass shell-and-tube heat exchangers and one-pass cross-flow exchangers.



c. *F* for a one-pass cross-flow exchanger with both passes unmixed.



d. *F* for a one-pass cross-flow exchanger with one pass mixed.

Figure 3.14 LMTD correction factors, *F*, for multipass shell-and-tube heat exchangers and one-pass cross-flow exchangers.

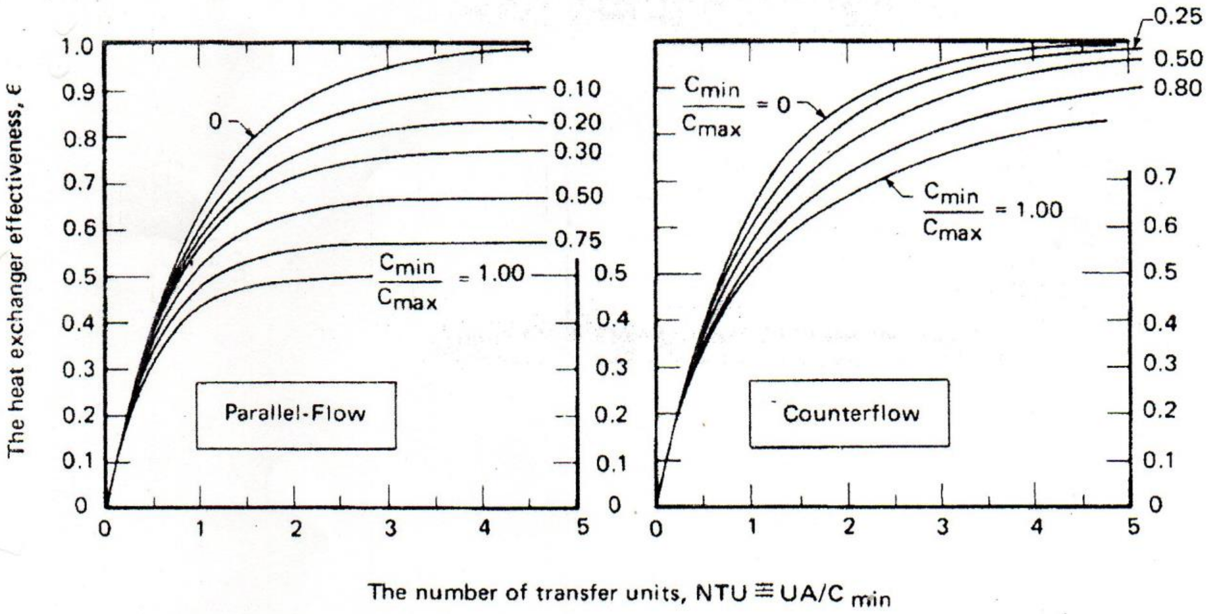
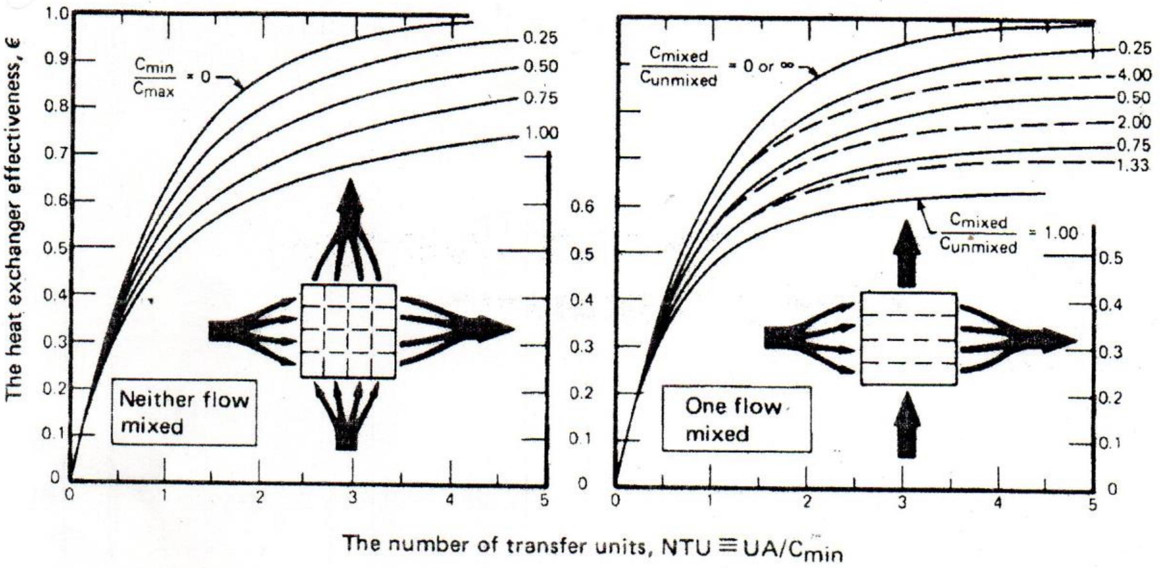
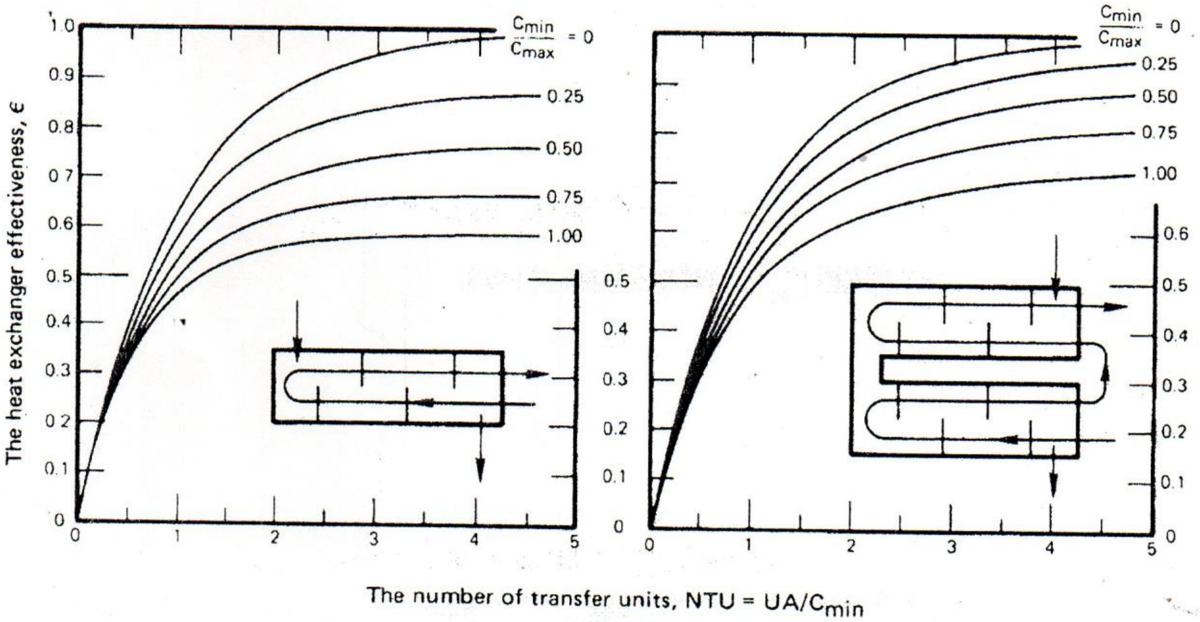


Figure The effectiveness of parallel and counterflow heat exchangers. (Data provided by A.D. Kraus.)



a.) Cross-flow exchanger, neither fluid mixed

b.) Cross-flow exchanger, one fluid mixed



c.) One shell pass, two tube pass exchanger. (Can also be used for 4, 6, 8, 10, 12 tube passes with a maximum error in ϵ, of 0.040 at $C_{min}/C_{max} = 1$ and large NTU.)

d.) Two shell pass 4 tube pass exchanger. (Can also be used for 4, 6, 8, ... tube passes with reasonable accuracy if there are equal numbers of tube passes in each shell pass.)

Figure . The effectiveness of some other heat exchanger configurations. (Data provided by A.D. Kraus.)

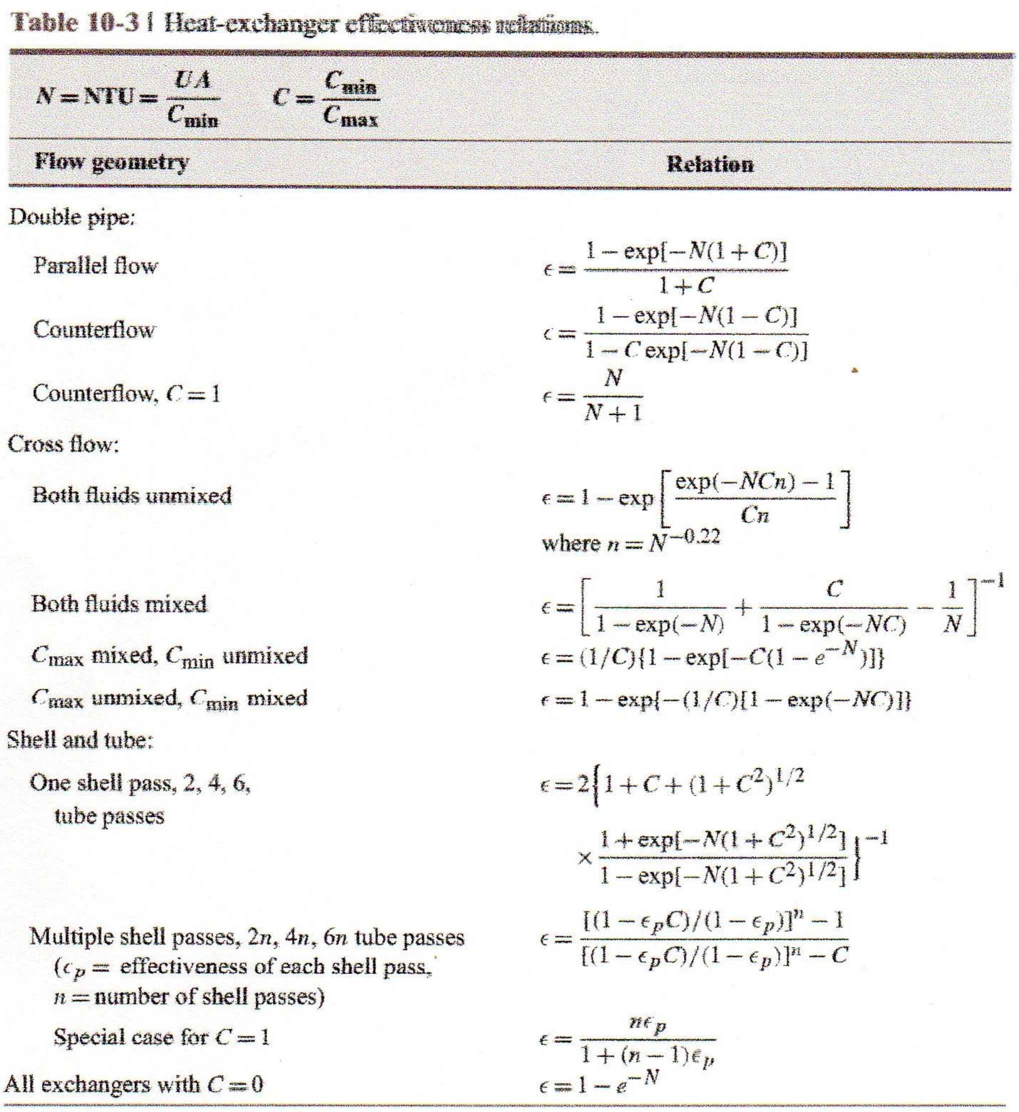


Table 10-3 | Heat-exchanger effectiveness relations.

$N = \text{NTU} = \dfrac{UA}{C_{\min}}$ $\qquad C = \dfrac{C_{\min}}{C_{\max}}$

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

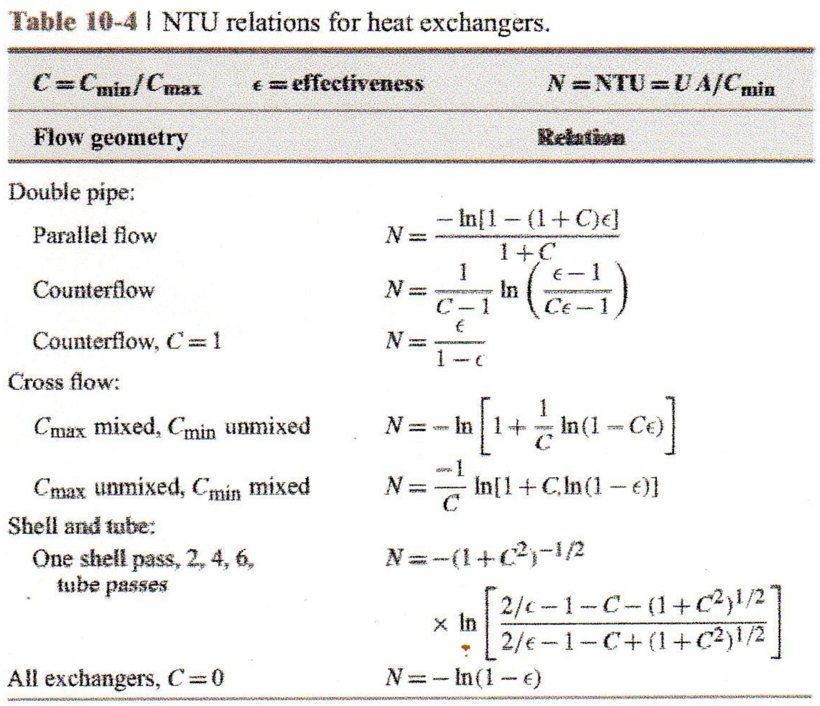
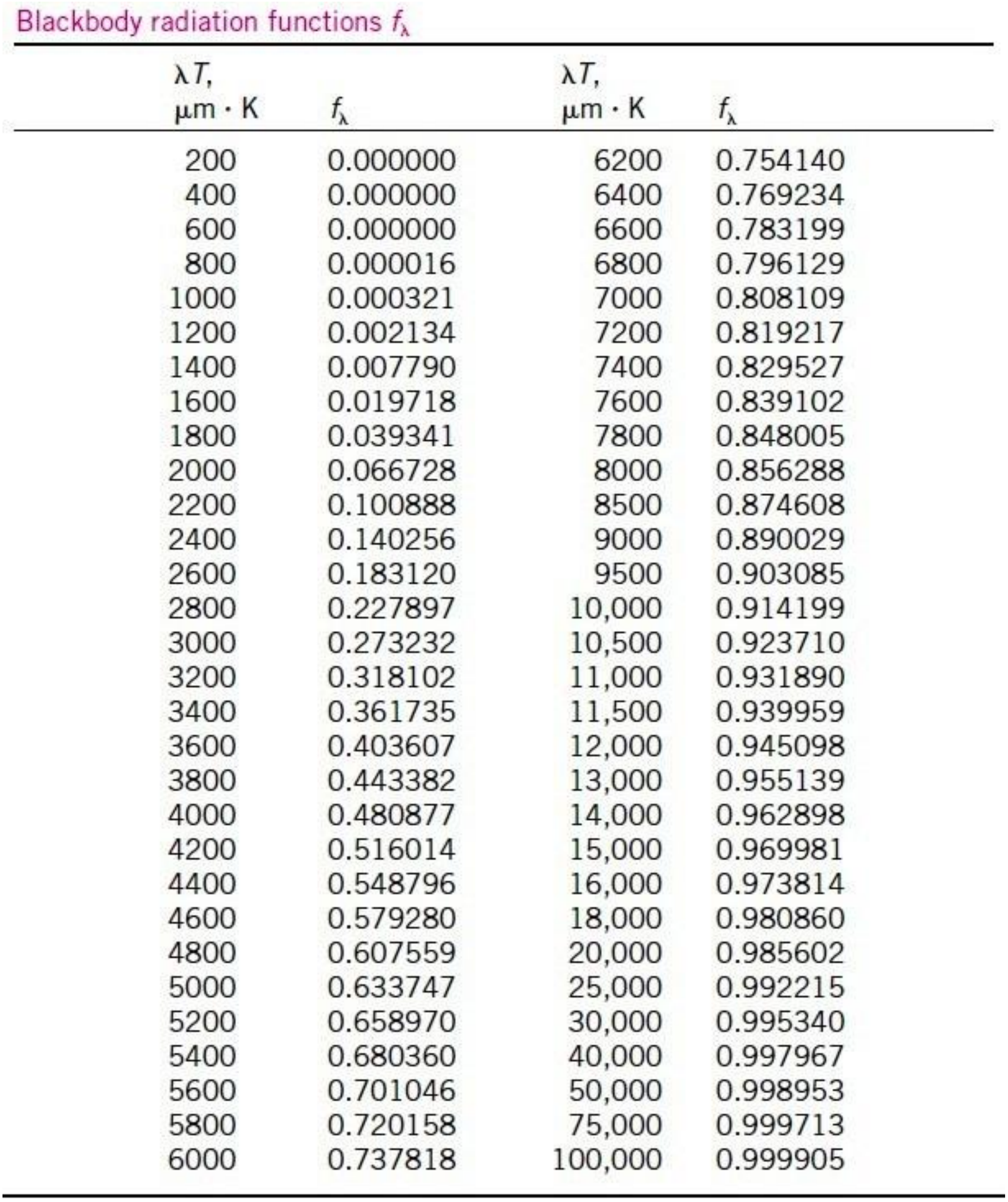


Table 10-4 | NTU relations for heat exchangers.

$C = C_{\min}/C_{\max}$ $\qquad \epsilon$ = effectiveness $\qquad N = \text{NTU} = UA/C_{\min}$

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



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