UNIVERSITI TEKNOLOGI PETRONAS

FINAL EXAMINATION
MAY 2024 SEMESTER

COURSE	**:**	**CEB1063/CFB1063 - PROCESS HEAT TRANSFER**
DATE	**:**	**1 AUGUST 2024 (THURSDAY)**
TIME	**:**	**9.00 AM - 12.00 NOON (3 HOURS)**

INSTRUCTIONS TO CANDIDATES

1. Answer **ALL** questions in the Answer Booklet.
2. Begin **EACH** answer on a new page in the Answer Booklet.
3. Indicate clearly answers that are cancelled, if any.
4. Where applicable, show clearly steps taken in arriving at the solutions and indicate **ALL** assumptions, if any.
5. **DO NOT** open this Question Booklet until instructed.

Note :

i. There are **TWENTY-TWO (22)** pages in this Question Booklet including the cover page and appendix.

ii. **DOUBLE-SIDED** Question Booklet.

1. Thermal resistance, defined in a similar form as the electric current flow in an electric circuit, is an important technique that can be applied in heat transfer.

a. The analysis of heat conduction through multi-layer solids assumed that a perfect contact exists between the interface layers. However, in a realistic case, the contact between surfaces is usually imperfect. With appropriate schematic diagram, explain how such a scenario will influence the resulting thermal resistance and heat transfer rate if the temperature difference across the multi-layer solids is equal.

[6 marks]

b. You are currently driving your car from Ipoh to Seri Iskandar to take the final exam that will be conducted at Chancellor Hall this morning. Consider that the car contains an engine cover that is made of stainless steel (k = 14 W/m·K) with a thickness and length of 1.5 mm and 2.1 m, respectively. The outer surface of the stainless steel is covered with 5.4-mm-thick insulation (k = 0.5 W/m·K). The inner surface of the engine cover is exposed to hot gas at 349°C with a convection heat transfer coefficient of 5.4 W/m^2·K. The outer surface of the insulation is subjected to the flow of air at 60°C, which is registered at the velocity of 7.8 m/s.

i. Based on the scenario above, illustrate the schematic diagram of the different layers and the thermal resistance network by providing appropriate temperature labels.

[8 marks]

ii. Determine the outer surface temperature of the insulation. Assume that the air film temperature is 120°C. State any additional assumptions in your calculation.

[11 marks]

2. Pipes and ducts are commonly utilized in various settings by taking various factors (e.g., geographical profile and safety) into consideration. Thus, it is required to understand the undesirable heat loss from the pipe.

   a. In general, there are **TWO (2)** possible thermal conditions that could be potentially present at the tube surface. Explain these thermal conditions by providing **ONE (1)** example.

   [6 marks]

   b. You are provided with two different circular pipes (Pipe #1 and Pipe #2) with different diameters and lengths. Determine the ratio of hydraulic diameter of these two circular pipes if the radius of pipe #1 is two times larger than pipe #2 and the length of pipe #2 is four times longer than pipe #1.

   [4 marks]

   c. Hot air at 1 atm and 90°C enters an uninsulated rough cast iron rectangular duct (length of 10.1 m) with a cross-section of 0.15 m × 0.21 m. The rectangular duct is used as the water heater in the washroom of the newly renovated house that you have purchased recently. The hot air is driven by a blower at the rate of 987 m^3/h. The outer surface temperature of the duct is measured at 60°C.

      i. Explain whether the properties of the fluid evaluated at the bulk mean temperature of 80°C are appropriate in this calculation.

      [4 marks]

      ii. Based on the scenario described above, determine the rate of heat loss and the percentage error based on the newly calculated exit temperature. State all the required assumptions in your calculation.

      [11 marks]

3. A steam turbine transforms the thermal energy in the steam into mechanical energy, which generates electrical energy through a generator. The main components of a steam turbine include a boiler, turbine, condenser, and generator.

   a. Explain the working principle of a boiler and a condenser.

   [6 marks]

   b. Water is boiled at 120°C by hot flue gas flowing through 40-m long and 4-cm outer diameter mechanically polished stainless-steel tubes. Using appropriate calculations, evaluate whether the boiler is at risk of burnout if the surface temperature of the tubes reaches 150°C.

   [7 marks]

   c. Exhaust steam exiting from the turbine enters the condenser at a low pressure of 31.19 kPa to recover the heat and water. The condenser consists of 100 horizontal tubes arranged in 10 × 10 square arrays where cooling water flows inside the tubes to maintain the surface temperature at 30°C. The tubes are 4 m long each and have an outer diameter of 3 cm. Determine the total rate of heat transfer from the steam to the cooling water and the rate of the condensation of steam in the condenser.

   [11 marks]

4. Heat exchangers are devices that allow the exchange of heat between two fluids without allowing them to mix with each other. There are several types of heat exchangers, the most commonly used are double pipe heat exchangers, plate heat exchangers, and shell and tube heat exchangers.

a. Define the effectiveness of a heat exchanger and discuss **TWO (2)** factors that affect the effectiveness of a heat exchanger.

[6 marks]

b. Consider a water-to-oil double-pipe heat exchanger whose flow arrangement is not known. The hot oil (c_p = 2200 J/kg·K) enters the heat exchanger at a flow rate of 2.1 kg/s at 130°C and leaves at 45°C, while the cold water (c_p = 4180 J/kg·K) enters at a flow rate of 1.5 kg/s at 30°C and leaves at a temperature higher than 45°C. Given the diameter of the thin-walled tube is 5 cm and the total length of the pipe is 20 m.

i. Evaluate whether the heat exchanger runs at a parallel or counter flow.

[6 marks]

ii. Determine the outlet temperature of the cold water and the effectiveness of the heat exchanger.

[7 marks]

iii. Using the LMTD method, determine the overall heat transfer coefficient of the heat exchanger.

[7 marks]

-END OF PAPER-

APPENDIX

<u>Equations</u>

$$R_{conv} = \frac{1}{hA}; R_{cond} = \frac{L}{kA}; R_{cond,cyl} = \frac{\ln(r_2/r_1)}{2\pi kL}; R_{cond,sph} = \frac{r_2 - r_1}{4\pi r_1 r_2 k}$$

$$Q = \frac{\Delta T}{R_{total}}$$

$$Q = hA_s(T_s - T_\infty)$$

$$Q = hA_s \Delta T_{lm}$$

$$Q = mc_p(T_e - T_i)$$

$$q = h(T_s - T_m)$$

$$\Delta T_{lm} = \frac{(T_s - T_e) - (T_s - T_i)}{\ln[(T_s - T_e)/(T_s - T_i)]}$$

$$T_e = T_s - (T_s - T_i)\exp\left(-\frac{A_s h}{mc_p}\right)$$

$$E = \frac{Q}{A} = \varepsilon\sigma T^4; \sigma = 5.67 \times 10^{-8} \frac{W}{m^2\,K^4}$$

$$E_{b\lambda}(\lambda, T) = \frac{2\pi hc_o^2}{\lambda^5[\exp(hc_o/\lambda kT) - 1]}; k = 1.3805 \times 10^{-23} \frac{J}{K}$$

$$(\lambda T)_{\text{max power}} = 2897.8\ \mu m\ K$$

$$Re = \frac{\rho V L_c}{\mu} = \frac{V L_c}{v}; Nu = \frac{hL_c}{k}$$

$$Ra = \frac{g\beta(T_s - T_\infty)L_c^3}{v^2} Pr$$

$$V = \frac{m}{\rho A_c}$$

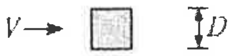
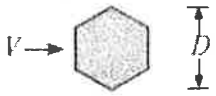
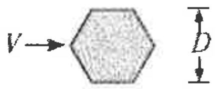
$$Pr = \frac{v}{\alpha} = \frac{\mu c_p}{k}$$

Correlations – Forced Convection

Geometry	Condition	Nu relation
Flow inside duct	Laminar (Re, < 2300), constant surface temperature	Nu = 3.66 (fully develop laminar region)
	Laminar (Re, < 2300), constant surface temperature	$Nu = 3.66 + \dfrac{0.065\left(\frac{D}{L}\right)Re_D Pr}{1 + 0.04\left[\left(\frac{D}{L}\right)Re_D Pr\right]^{\frac{2}{3}}}$ (developing flow)
	Laminar (Re, < 2300), constant surface heat flux	Nu = 4.36 (fully develop laminar region)
	Turbulent, smooth pipe (Re > 10,000)	$Nu = 0.023Re^{0.8}Pr^{n}$ (fully developed turbulent region) n = 0.3 for cooling, n = 0.4 for heating
	Turbulent, rough pipe $3000 \le Re_D \le 5 \times 10^6$ $0.5 \le Pr \le 2000$	$\mathrm{Nu_D} = \dfrac{\left(\frac{f}{8}\right)(\mathrm{Re_D} - 1000)\mathrm{Pr}}{1 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(\mathrm{Pr}^{\frac{2}{3}} - 1\right)}$
	Friction factor, rough pipe	$\dfrac{1}{\sqrt{f}} = -2.0\,log_{10}\left[\dfrac{\varepsilon/D}{3.7} + \dfrac{2.51}{Re_D\sqrt{f}}\right] \approx -1.8\,log_{10}\left[\dfrac{6.9}{Re_D} + \left(\dfrac{\varepsilon/D}{3.7}\right)^{1.11}\right]$
	Friction factor, smooth pipe	$f = (0.790\ln \mathrm{Re_D} - 1.64)^{-2}$
	Entry length	$L_h = L_t = 10D$ (turbulent) $L_h = L_t Pr = 0.05RePrD$ (laminar)
	Hydraulic diameter, D_h	$D_h = \dfrac{4A_c}{P}$
Flow over flat plate	Laminar Flow ($\mathrm{Re_L} < 5 \times 10^5$)	$\mathrm{Nu} = 0.664\mathrm{Re_L^{0.5}}\mathrm{Pr}^{\frac{1}{3}}$
	Turbulent Flow	$\mathrm{Nu} = 0.037\mathrm{Re_L^{0.5}}\mathrm{Pr}^{\frac{1}{3}}$
	Average Nusselt number for entire plate	$\mathrm{Nu} = (0.037\mathrm{Re_L^{0.8}} - 871)\mathrm{Pr}^{\frac{1}{3}}$
Flow over circular cylinder	$RePr$ > 0.2	$Nu = 0.3 + \dfrac{0.62Re^{\frac{1}{2}}Pr^{\frac{1}{3}}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}}\left\{1 + \left(\dfrac{Re}{282{,}000}\right)^{\frac{5}{8}}\right\}^{\frac{4}{5}}$
Flow over sphere	$3.5 \le Re \le 80000$ $0.7 \le Pr \le 380$	$Nu = 2 + \left[0.4Re^{\frac{1}{2}} + 0.06Re^{\frac{2}{3}}\right]Pr^{0.4}\left(\dfrac{\mu}{\mu_s}\right)^{\frac{1}{4}}$
Flow over tube bank	V_{max}, for $S_D > (\mathrm{S_T} + \mathrm{D})/2$	$\mathrm{V_{max}} = \dfrac{\mathrm{S_T}}{2(\mathrm{S_D} - \mathrm{D})}\mathrm{V}$
	V_{max}, for $S_D < (\mathrm{S_T} + \mathrm{D})/2$	$\mathrm{V_{max}} = \dfrac{\mathrm{S_T}}{\mathrm{S_T} - \mathrm{D}}\mathrm{V}$

Laminar flow for external flow in non-circular cylinder

$$Nu = CRe_D^m Pr^{\frac{1}{3}}$$

Geometry	Re_D	C	m
Square			
	5×10^3–10^5	0.246	0.588
	5×10^3–10^5	0.102	0.675
Hexagon			
	5×10^3–1.95×10^4 1.95×10^4–10^5	0.160 0.0385	0.638 0.782
	5×10^3–10^5	0.153	0.638
Vertical plate			
	4×10^3–1.5×10^4	0.228	0.731

Flow across tube bank

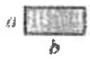
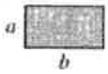
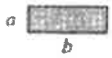
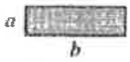
1. Nusselt number correlations for $N_L > 16$ and $0.7 < Pr < 500$

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	$Nu_D = 0.52\, Re_D^{0.5} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	1000–2×10^5	$Nu_D = 0.27\, Re_D^{0.63} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	2×10^5–2×10^6	$Nu_D = 0.033\, Re_D^{0.8} Pr^{0.4} (Pr/Pr_s)^{0.25}$
Staggered	0–500	$Nu_D = 1.04\, Re_D^{0.4} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	500–1000	$Nu_D = 0.71\, Re_D^{0.5} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	1000–2×10^5	$Nu_D = 0.35 (S_T/S_L)^{0.2}\, Re_D^{0.6} Pr^{0.36} (Pr/Pr_s)^{0.25}$
	2×10^5–2×10^6	$Nu_D = 0.031 (S_T/S_L)^{0.2}\, Re_D^{0.8} Pr^{0.36} (Pr/Pr_s)^{0.25}$

2. Correction factor, F

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

Laminar flow for internal flow in circular and non-circular tube

Cross Section	$\frac{b}{a}$	$Nu_D = \frac{hD_h}{k}$ (Uniform q''_s)	(Uniform T_s)	$f\,Re_{D_h}$
	—	4.36	3.66	64
	1.0	3.61	2.98	57
	1.43	3.73	3.08	59
	2.0	4.12	3.39	62
	3.0	4.79	3.96	69
	4.0	5.33	4.44	73
	8.0	6.49	5.60	82
	∞	8.23	7.54	96
Heated  Insulated	∞	5.39	4.86	96
	—	3.11	2.47	53

Roughness ratio/relative roughness of the commercial pipe

Equivalent roughness values for new commercial pipes*

Material	Roughness, ε ft	mm
Glass, plastic	0 (smooth)	
Concrete	0.003–0.03	0.9–9
Wood stave	0.0016	0.5
Rubber, smoothed	0.000033	0.01
Copper or brass tubing	0.000005	0.0015
Cast iron	0.00085	0.26
Galvanized iron	0.0005	0.15
Wrought iron	0.00015	0.046
Stainless steel	0.000007	0.002
Commercial steel	0.00015	0.045

Correlations – Natural Convection

Geometry	Condition	Nu relation
Vertical plate	$10^4 \le Ra \le 10^9$	$Nu = 0.59Ra_L^{\frac{1}{4}}$
	$10^{10} \le Ra \le 10^{13}$	$Nu = 0.1Ra_L^{\frac{1}{3}}$
	Entire range	$Nu = \left\{0.825 + \frac{0.387Ra_L^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right\}^2$
Inclined plate	(similar to vertical plate)	For $0 < \theta < 60^o$, replace g with $g\cos\theta$
Horizontal plate (upper surface of a hot plate or lower surface of a cold plate)	$10^4 \le Ra \le 10^7$	$Nu = 0.59Ra_L^{\frac{1}{4}}$
	$10^7 \le Ra \le 10^{11}$	$Nu = 0.1Ra_L^{\frac{1}{3}}$
Horizontal plate (lower surface of a hot plate or upper surface of a cold plate	$10^5 \le Ra \le 10^{11}$	$Nu = 0.27Ra_L^{\frac{1}{4}}$
Vertical cylinder	N.A.	It can be treated as vertical plate if: $D \ge \frac{35L}{Gr_L^{\frac{1}{4}}}$
Horizontal cylinder	$Ra_D \le 10^{12}$	$Nu = \left\{0.6 + \frac{0.387Ra_D^{\frac{1}{6}}}{\left[1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right\}^2$
Sphere	$Ra_D \le 10^{11}$ $Pr \ge 0.7$	$Nu = 2 + \frac{0.589Ra_D^{\frac{1}{4}}}{\left[1 + \left(\frac{0.469}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}}$

Boiling and Condensation

Condition	Correlation
Boiling	$q_{boiling} = hA_s(T_s - T_{excess}) = hA_s\Delta T_{excess}$
	$q_{nucleate} = \mu_l h_{fg}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{\frac{1}{2}}\left[\frac{c_{pl}(T_s - T_{sat})}{C_{sf}h_{fg}Pr_l^n}\right]^3$
	$q_{max} = C_{cr}h_{fg}[\sigma g\rho_v^2(\rho_l - \rho_v)]^{\frac{1}{4}}$
	$q_{film} = C_{film}\left[\frac{gk_v^3\rho_v(\rho_l - \rho_v)[h_{fg} + 0.4c_{pv}(T_s - T_{sat})]}{\mu_v D(T_s - T_{sat})}\right]^{\frac{1}{4}}(T_s - T_{sat})$ $C_{film} = 0.62$ (Horizontal cylinders) $C_{film} = 0.67$ (Spheres)
Condensation	$h_{fg}^* = h_{fg} + 0.68c_{pl}(T_{sat} - T_s)$ $Q_{condensation} = hA_s(T_{sat} - T_s) = mh_{fg}^*$
	Laminar flow on vertical plate (0 < Re < 30) $Re_{vert} = \frac{4g}{3v_l^2}\left(\frac{k_l}{3h_{vert}/4}\right)^3$ $h_{vert} = 0.943\left[\frac{g(\rho_l - \rho_v)[h_{fg}^* k_l^3]}{\mu_l(T_s - T_{sat})L}\right]^{\frac{1}{4}}$
	Wavy laminar flow on vertical plate (30 < Re < 1800) $Re_{vert,wavy} = \left[4.81 + \frac{3.70Lk_l(T_{sat} - T_s)}{\mu_l h_{fg}^*}\left(\frac{g}{v_l^2}\right)^{\frac{1}{3}}\right]^{0.82}$ $h_{vert,wavy} = \frac{Rek_l}{1.08Re^{1.22} - 5.2}\left(\frac{g}{v_l^2}\right)^{\frac{1}{3}}$
	Turbulent flow on vertical plate (Re > 1800) $Re_{vert,turbulent} = \left[\frac{0.0690Lk_l Pr^{0.5}(T_{sat} - T_s)}{\mu_l h_{fg}^*}\left(\frac{g}{v_l^2}\right)^{\frac{1}{3}} - 151Pr^{0.5} + 253\right]^{\frac{4}{3}}$ $h_{vert,turbulent} = \frac{Rek_l}{8750 + 58Pr^{-0.5}(Re^{0.75} - 253)}\left(\frac{g}{v_l^2}\right)^{\frac{1}{3}}$
	Laminar and wavy laminar on tilted vertical plate $h_{tilt} = h_{vert}(\cos\theta)^{\frac{1}{4}}$
	Single horizontal and vertical tube $h_{horiz} = 0.729\left[\frac{g\rho_l(\rho_l - \rho_v)[h_{fg}^* k_l^3]}{\mu_l(T_s - T_{sat})D}\right]^{\frac{1}{4}}$ $\frac{h_{vert}}{h_{horiz}} = 1.29\left[\frac{D}{L}\right]^{\frac{1}{4}}$

	Sphere $h_{sph} = 0.815\left[\frac{g(\rho_l-\rho_v)[h^*_{fg}k_l^3]}{\mu_l(T_s-T_{sat})D}\right]^{\frac{1}{4}}$
	Horizontal tube bank $h_{horiz,N\ tubes} = 0.729\left[\frac{g(\rho_l-\rho_v)[h^*_{fg}k_l^3]}{\mu_l(T_s-T_{sat})ND}\right]^{\frac{1}{4}} = \frac{1}{N^{\frac{1}{4}}}h_{horiz,1\ tube}$

Heat Exchanger

Condition	**Correlation**
Overall heat transfer coefficient	$\frac{1}{UA_s} = \frac{1}{U_iA_i} = \frac{1}{U_oA_o}$ $R = \frac{1}{h_iA_i} + \frac{R_{f,i}}{A_i} + \frac{\ln(D_o/D_i)}{2\pi kL} + \frac{R_{f,o}}{A_o} + \frac{1}{h_oA_o}$ For thin-walled tube: $\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o}$
Heat transfer	$Q = m_cc_{pc}(T_{c,out} - T_{c,in}) = m_hc_{ph}(T_{h,in} - T_{h,out})$ $Q_{max} = C_{min}(T_{h,in} - T_{c,in})$ $Q = UA_sF\Delta T_{lm,CF}$ $\Delta T_{lm,CF} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$
Parallel flow	$\Delta T_1 = T_{h,in} - \Delta T_{c,in}$ $\Delta T_2 = T_{h,out} - \Delta T_{c,out}$
Counter flow	$\Delta T_1 = T_{h,in} - \Delta T_{c,out}$ $\Delta T_2 = T_{h,out} - \Delta T_{c,in}$
Cross flow and multipass	$\Delta T_1 = T_{h,in} - \Delta T_{c,in}$ $\Delta T_2 = T_{h,out} - \Delta T_{c,out}$
Effectiveness relation	$c = C_{min}/C_{max}$ $NTU = UA_s/C_{min}$ $C_h = m_hc_{ph}$; $C_c = m_cc_{pc}$

Blackbody radiation function, f_λ

$$f_\lambda(T) = \frac{\int_0^\lambda E_{b\lambda}(\lambda,T)\,d\lambda}{\sigma T^4}$$

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

Properties of saturated propane

Properties of saturated propane

Temp. T, °C	Saturation Pressure P, 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	Surface Tension, N/m
−120	0.4053	664.7	0.01408	498.3	2003	1115	0.1802	0.00589	6.136×10^{-4}	4.372×10^{-6}	6.820	0.827	0.00153	0.02630
−110	1.157	654.5	0.03776	489.3	2021	1148	0.1738	0.00645	5.054×10^{-4}	4.625×10^{-6}	5.878	0.822	0.00157	0.02486
−100	2.881	644.2	0.08872	480.4	2044	1183	0.1672	0.00705	4.252×10^{-4}	4.881×10^{-6}	5.195	0.819	0.00161	0.02344
−90	6.406	633.8	0.1870	471.5	2070	1221	0.1606	0.00769	3.635×10^{-4}	5.143×10^{-6}	4.686	0.817	0.00166	0.02202
−80	12.97	623.2	0.3602	462.4	2100	1263	0.1539	0.00836	3.149×10^{-4}	5.409×10^{-5}	4.297	0.817	0.00171	0.02062
−70	24.26	612.5	0.6439	453.1	2134	1308	0.1472	0.00908	2.755×10^{-4}	5.680×10^{-6}	3.994	0.818	0.00177	0.01923
−60	42.46	601.5	1.081	443.5	2173	1358	0.1407	0.00985	2.430×10^{-4}	5.956×10^{-5}	3.755	0.821	0.00184	0.01785
−50	70.24	590.3	1.724	433.6	2217	1412	0.1343	0.01067	2.158×10^{-4}	6.239×10^{-6}	3.563	0.825	0.00192	0.01649
−40	110.7	578.8	2.629	423.1	2258	1471	0.1281	0.01155	1.926×10^{-4}	6.529×10^{-6}	3.395	0.831	0.00201	0.01515
−30	167.3	567.0	3.864	412.1	2310	1535	0.1221	0.01250	1.726×10^{-4}	6.827×10^{-6}	3.266	0.839	0.00213	0.01382
−20	243.8	554.7	5.503	400.3	2368	1605	0.1163	0.01351	1.551×10^{-4}	7.136×10^{-6}	3.158	0.848	0.00226	0.01251
−10	344.4	542.0	7.635	387.8	2433	1682	0.1107	0.01459	1.397×10^{-4}	7.457×10^{-6}	3.069	0.860	0.00242	0.01122
0	473.3	528.7	10.36	374.2	2507	1768	0.1054	0.01576	1.259×10^{-4}	7.794×10^{-6}	2.996	0.875	0.00262	0.00996
5	549.8	521.8	11.99	367.0	2547	1814	0.1028	0.01637	1.195×10^{-4}	7.970×10^{-6}	2.964	0.883	0.00273	0.00934
10	635.1	514.7	13.81	359.5	2590	1864	0.1002	0.01701	1.135×10^{-4}	8.151×10^{-6}	2.935	0.893	0.00286	0.00872
15	729.8	507.5	15.85	351.7	2637	1917	0.0977	0.01767	1.077×10^{-4}	8.339×10^{-6}	2.909	0.905	0.00301	0.00811
20	834.4	500.0	18.13	343.4	2688	1974	0.0952	0.01836	1.022×10^{-4}	8.534×10^{-6}	2.886	0.918	0.00318	0.00751
25	949.7	492.2	20.68	334.8	2742	2036	0.0928	0.01908	9.702×10^{-5}	8.738×10^{-6}	2.866	0.933	0.00337	0.00691
30	1076	484.2	23.53	325.8	2802	2104	0.0904	0.01982	9.197×10^{-5}	8.952×10^{-6}	2.850	0.950	0.00358	0.00633
35	1215	475.8	26.72	316.2	2869	2179	0.0881	0.02061	8.710×10^{-5}	9.178×10^{-6}	2.837	0.971	0.00384	0.00575
40	1366	467.1	30.29	306.1	2943	2264	0.0857	0.02142	8.240×10^{-5}	9.417×10^{-6}	2.828	0.995	0.00413	0.00518
45	1530	458.0	34.29	295.3	3026	2361	0.0834	0.02228	7.785×10^{-5}	9.674×10^{-6}	2.824	1.025	0.00448	0.00463
50	1708	448.5	38.79	283.9	3122	2473	0.0811	0.02319	7.343×10^{-5}	9.950×10^{-5}	2.826	1.061	0.00491	0.00408
60	2110	427.5	49.66	258.4	3283	2769	0.0765	0.02517	6.487×10^{-5}	1.058×10^{-5}	2.784	1.164	0.00609	0.00303
70	2580	403.2	64.02	228.0	3595	3241	0.0717	0.02746	5.649×10^{-5}	1.138×10^{-5}	2.834	1.343	0.00811	0.00204
80	3127	373.0	84.28	189.7	4501	4173	0.0663	0.03029	4.790×10^{-5}	1.249×10^{-5}	3.251	1.722	0.01248	0.00114
90	3769	329.1	118.6	133.2	6977	7239	0.0595	0.03441	3.807×10^{-5}	1.448×10^{-5}	4.465	3.047	0.02847	0.00037

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 properties listed here (except the vapor density) can be used at any pressures 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: Data generated from the EES software developed by S. A. Klein and F. L. Alvarado. Original sources: Reiner Tillner-Roth, "Fundamental Equations of State," Shaker, Verlag, Aachan, 1998; B. A. Younglove and J. F. Ely, "Thermophysical Properties of Fluids. II Methane, Ethane, Propane, Isobutane, and Normal Butane," *J. Phys. Chem. Ref. Data*, Vol. 16, No. 4, 1987; G.R. Somayajulu, "A Generalized Equation for Surface Tension from the Triple-Point to the Critical-Point," *International Journal of Thermophysics*, Vol. 9, No. 4, 1988.

Properties of air at 1 atm pressure

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

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}			

Thermal conductivity of several materials

Material	k, W/m · °C*
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.613
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

A

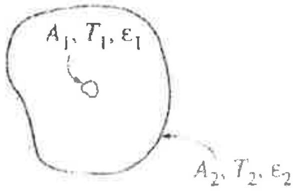
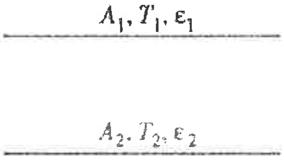
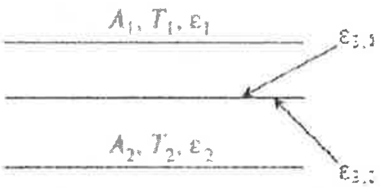
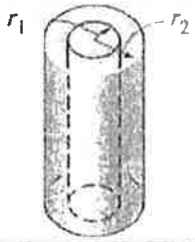
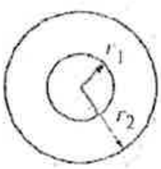
Convection heat transfer coefficient

Type of convection	h, W/m^2 · °C*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

Emissivity of several materials at 300 K

Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

Radiation heat transfer in two-surface enclosures

Geometry	Conditions	Rate of heat transfer
Small object in a large cavity 	$\frac{A_1}{A_2} \approx 0$ $F_{12} = 1$	$\dot{Q}_{12} = A_1\sigma\varepsilon_1(T_1^4 - T_2^4)$
Infinitely large parallel plates 	$A_1 = A_2 = A$ $F_{12} = 1$	$\dot{Q}_{12} = \frac{A\sigma(T_1^4 - T_2^4)}{\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right)}$
	$A_1 = A_2 = A$ $F_{12} = 1$	$\dot{Q}_{12} = \frac{A\sigma(T_1^4 - T_2^4)}{\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right) + \left(\frac{1}{\varepsilon_{3,1}} + \frac{1}{\varepsilon_{3,2}} - 1\right) + \dots}$
Infinitely long concentric cylinders 	$\frac{A_1}{A_2} = \frac{r_1}{r_2}$ $F_{12} = 1$	$\dot{Q}_{12} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)}$
Concentric spheres 	$\frac{A_1}{A_2} = \left(\frac{r_1}{r_2}\right)^2$ $F_{12} = 1$	$\dot{Q}_{12} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)^2}$

where

$\dot{Q}_{12}$ = heat transfer rate, W
A = area, m
T = temperature, K
ε = emissivity
r = radius, m

Surface tension of liquid-vapor interface for water

T, °C	σ, N/m*
0	0.0757
20	0.0727
40	0.0696
60	0.0662
80	0.0627
100	0.0589
120	0.0550
140	0.0509
160	0.0466
180	0.0422
200	0.0377
220	0.0331
240	0.0284
260	0.0237
280	0.0190
300	0.0144
320	0.0099
340	0.0056
360	0.0019
374	0.0

Surface tension of some fluids

Surface tension of some fluids (from Suryanarayana, 1995, originally based on data from Jasper, 1972)

Substance and Temp. Range	Surface Tension, σ, N/m* (T in °C)
Ammonia, −75 to −40°C:	$0.0264 + 0.000223T$
Benzene, 10 to 80°C:	$0.0315 - 0.000129T$
Butane, −70 to −20°C:	$0.0149 - 0.000121T$
Carbon dioxide, −30 to −20°C:	$0.0043 - 0.000160T$
Ethyl alcohol, 10 to 70°C:	$0.0241 - 0.000083T$
Mercury, 5 to 200°C:	$0.4906 - 0.000205T$
Methyl alcohol, 10 to 60°C:	$0.0240 - 0.000077T$
Pentane, 10 to 30°C:	$0.0183 - 0.000110T$
Propane, −90 to −10°C:	$0.0092 - 0.000087T$

*Multiply by 0.06852 to convert to lbf/ft or by 2.2046 to convert to lbm/s²

Values of coefficient C_{sf} and n for various fluid-surface combination

Fluid–Heating Surface Combination	C_{sf}	n
Water–copper (polished)	0.0130	1.0
Water–copper (scored)	0.0068	1.0
Water–stainless steel (mechanically polished)	0.0130	1.0
Water–stainless steel (ground and polished)	0.0060	1.0
Water–stainless steel (teflon pitted)	0.0058	1.0
Water–stainless steel (chemically etched)	0.0130	1.0
Water–brass	0.0060	1.0
Water–nickel	0.0060	1.0
Water–platinum	0.0130	1.0
n-Pentane–copper (polished)	0.0154	1.7
n-Pentane–chromium	0.0150	1.7
Benzene–chromium	0.1010	1.7
Ethyl alcohol–chromium	0.0027	1.7
Carbon tetrachloride–copper	0.0130	1.7
Isopropanol–copper	0.0025	1.7

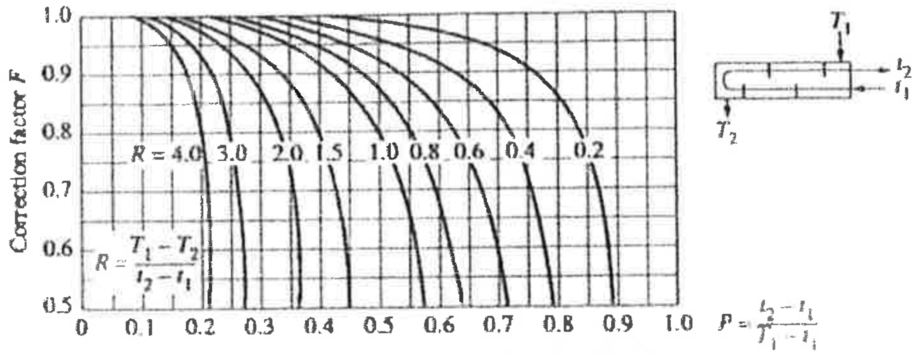
Values of coefficient C_{cr}

Values of the coefficient C_{cr} for use in Eq. 10–3 for maximum heat flux (dimensionless parameter $L^* = L[g(\rho_l - \rho_v)/\sigma]^{1/2}$)

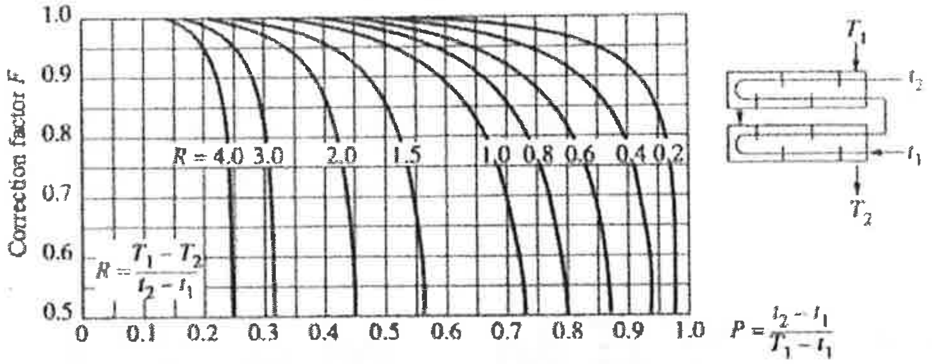
Heater Geometry	C_{cr}	Charac. Dimension of Heater, L	Range of L^*
Large horizontal flat heater	0.149	Width or diameter	$L^* > 27$
Small horizontal flat heater[1]	$18.9K_1$	Width or diameter	$9 < L^* < 20$
Large horizontal cylinder	0.12	Radius	$L^* > 1.2$
Small horizontal cylinder	$0.12L^{*-0.25}$	Radius	$0.15 < L^* < 1.2$
Large sphere	0.11	Radius	$L^* > 4.26$
Small sphere	$0.227L^{*-0.5}$	Radius	$0.15 < L^* < 4.26$

[1] $K_1 = \sigma/[g(\rho_l - \rho_v)A_{heater}]$

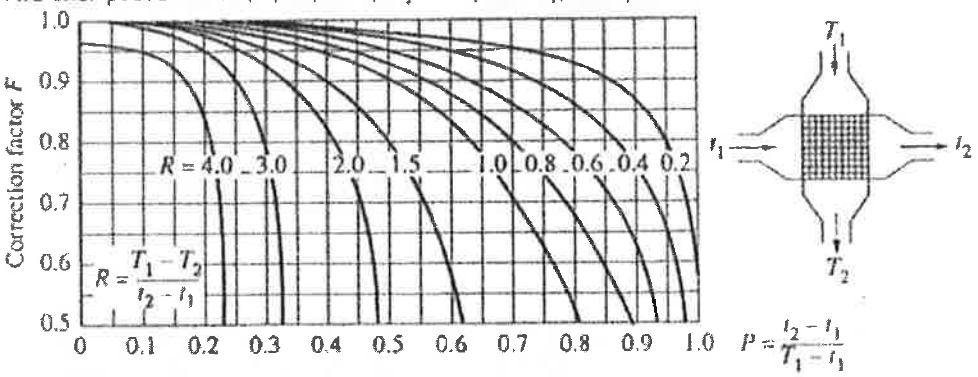
LMTD Correction factor chart for common shell-and-tube and cross flow heat exchanger



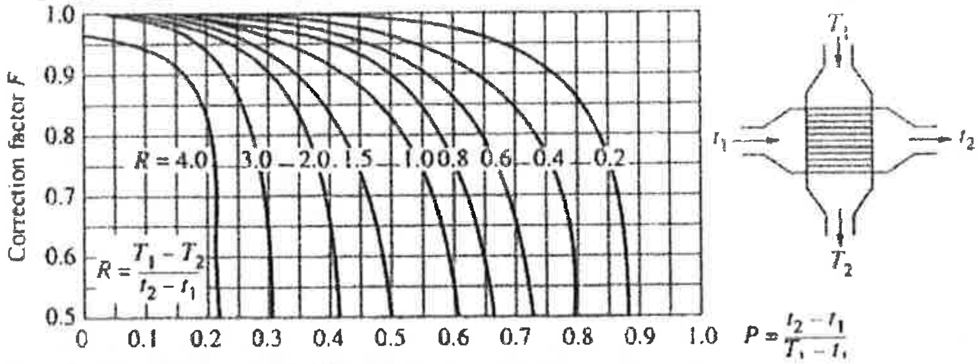
One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes



Two-shell passes and 4, 8, 12, etc. (any multiple of 4), tube passes

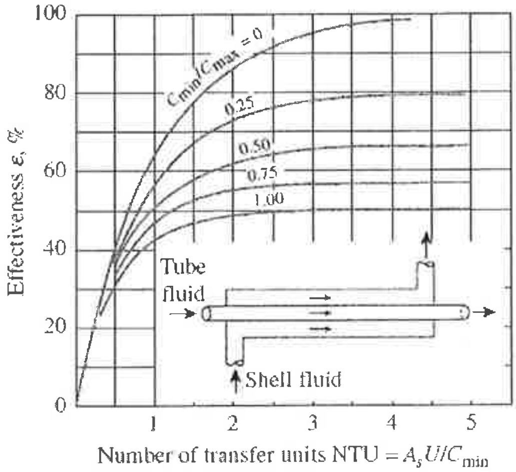


Single-pass cross-flow with both fluids unmixed

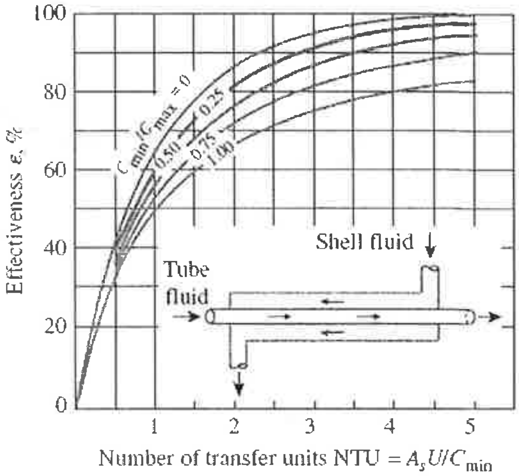


Single-pass cross-flow with one fluid mixed and the other unmixed

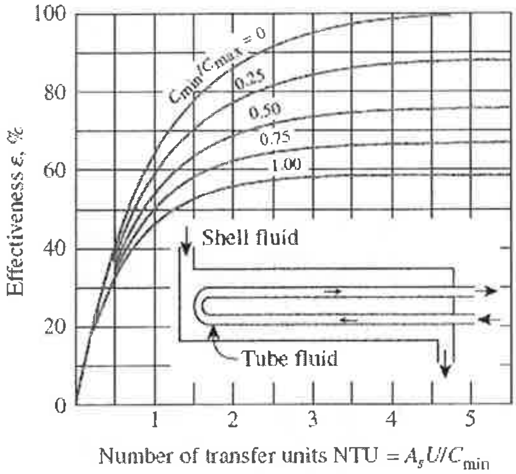
Effectiveness of heat exchanger



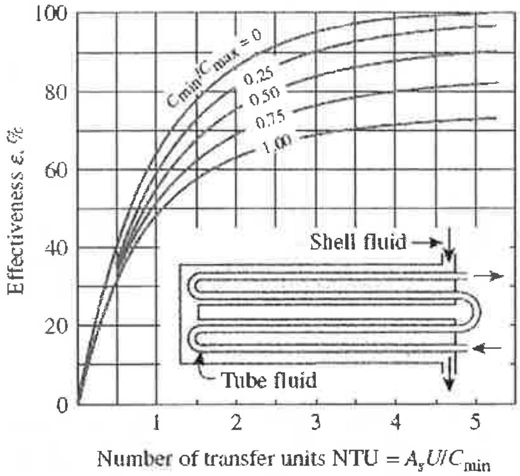
(*a*) Parallel-flow



(*b*) Counter-flow



(*c*) One-shell pass and 2, 4, 6, … tube passes



(*d*) Two-shell passes and 4, 8, 12, … tube passes

Effectiveness relations for heat exchanger

Heat exchanger type	Effectiveness relation
1 *Double pipe:*	
Parallel-flow	$\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1 + c)]}{1 + c}$
Counter-flow	$\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1 - c)]}{1 - c\exp[-\text{NTU}(1 - c)]}$ (for $c < 1$)
	$\varepsilon = \dfrac{\text{NTU}}{1 + \text{NTU}}$ (for $c = 1$)
2 *Shell-and-tube:* One-shell pass 2, 4,...tube passes	$\varepsilon_1 = 2\left\{1 + c + \sqrt{1 + c^2}\,\dfrac{1 + \exp\left[-\text{NTU}_1\sqrt{1 + c^2}\right]}{1 - \exp\left[-\text{NTU}_1\sqrt{1 + c^2}\right]}\right\}^{-1}$
n-shell passes 2*n*, 4*n*, ... tube passes	$\varepsilon_n = \left[\left(\dfrac{1 - \varepsilon_1 c}{1 - \varepsilon_1}\right)^n - 1\right]\left[\left(\dfrac{1 - \varepsilon_1 c}{1 - \varepsilon_1}\right)^n - c\right]^{-1}$
3 *Cross-flow (single-pass)* Both fluids unmixed	$\varepsilon = 1 - \exp\left\{\dfrac{\text{NTU}^{0.22}}{c}\left[\exp(-c\text{NTU}^{0.78}) - 1\right]\right\}$
C_{max} mixed, C_{min} unmixed	$\varepsilon = \dfrac{1}{c}(1 - \exp\{-c[1 - \exp(-\text{NTU})]\})$
C_{min} mixed, C_{max} unmixed	$\varepsilon = 1 - \exp\left\{-\dfrac{1}{c}[1 - \exp(-c\,\text{NTU})]\right\}$
4 *All heat exchangers with c = 0*	$\varepsilon = 1 - \exp(-\text{NTU})$