TRANSPORT PHENOMENA
CHAPTER 4

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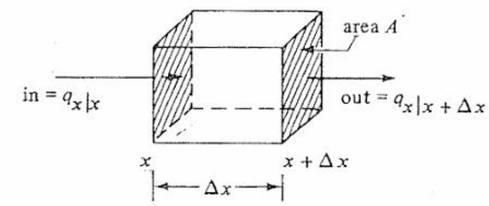
- ## General Thermal Energy Balance Equation

(Rate of heat in) + (Rate of heat generation) = (Rate of heat out) + (Rate of heat accumulation)

$$q_x|_x + \dot{q}(\Delta x. A) = q_x|_{x+\Delta x} + \rho\, C_p \frac{\partial T}{\partial t} (\Delta x. A)$$



- ## At steady-state with no heat generation:

(Rate of heat in) = (Rate of heat out)

$$q_x|_x = q_x|_{x+\Delta x}$$

- ## Fourier's Law of Heat Conduction:

Rate of a transfer process = $\frac{\text{Driving force}}{Resistance}$

$$\frac{q_x}{A} = -\,k\,\frac{dT}{dx}$$

T: Temperature [=] K

X: Distance [=] m

K: Thermal conductivity [=] W/m. K

A: Cross-sectional area normal to direction of heat flow [=] m^2

q_x: Heat-transfer rate in x-direction [=] W

$\frac{q_x}{A}$: Heat flux [=] W/m^2

$\frac{dT}{dx}$: Temperature gradient in the x-direction.

- For the case of steady-state heat transfer through a flat wall of constant cross-sectional area, A:

$$\frac{q_x}{A} = \int_{x_1}^{x_2} dx = -\,k \int_{T_1}^{T_2} dT$$

$$\frac{q_x}{A}(x_2 - x_1\,) = -\,k\,(T_2 - T_1)$$

- When the fluid outside the solid surface is in forced or natural convective motion, we express the rate of heat transfer from the solid to the fluid, or vice versa, by:

$$q = h\,A\,(T_w - T_f)$$

q: Heat-transfer rate [=] W
h: Convective heat-transfer coefficient [=] W/m^2.K
A: Area [=] m^2
T_w: Temperature of solid surface [=] K
T_f: Average (bulk) temperature of the fluid flowing by [=] K

- Conduction Heat Transfer

A. Through a Flat Slab or Wall

$$q = \frac{T_1 - T_2}{\frac{\Delta x}{kA}}$$

$$R = \frac{\Delta x}{kA}$$ [=] K/W

B. Through a Hollow Cylinder

$$q = \frac{T_1 - T_2}{\frac{r_2 - r_1}{kA_{lM}}}$$

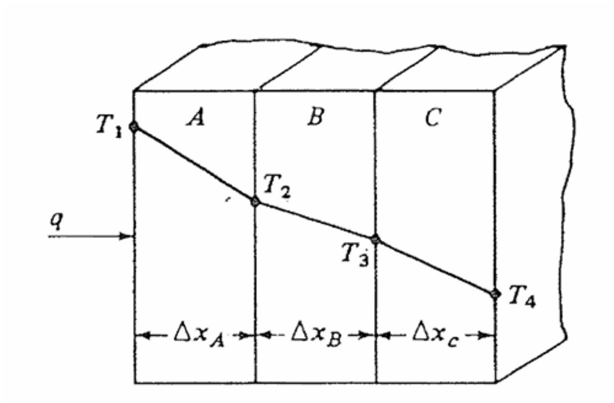
$$R = \frac{r_2 - r_1}{kA_{lM}} = \frac{ln(r_2/r_1)}{2\pi kL}$$ [=] K/W

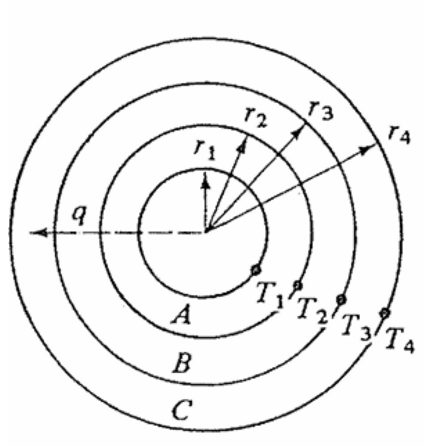
C. Through a Hollow Sphere

$$q = \frac{T_1 - T_2}{\frac{(\frac{1}{r_1} - \frac{1}{r_2})}{4\pi k}}$$

$$R = \frac{(\frac{1}{r_1} - \frac{1}{r_2})}{4\pi k}$$ [=] K/W

- CONDUCTION THROUGH SOLIDS IN SERIES





$$R = \frac{\Delta x}{kA}$$

$$q = \frac{T_1 - T_4}{\sum R}$$

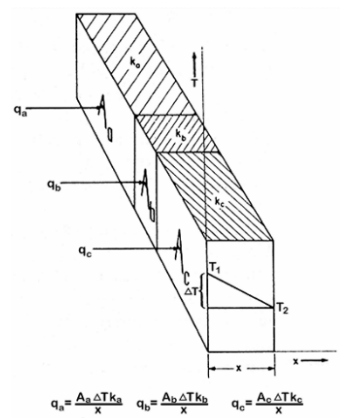
$$R = \frac{r_2 - r_1}{kA_{lM}}$$

- Conduction Through Materials in Parallel

$$q_T = q_1 + q_2$$

If $T_1 = T_2$, *and* $T_3 = T_4$

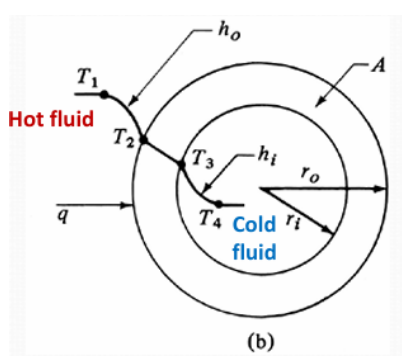
$$q_T = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)(T_1 - T_2)$$



- Combined Convection and Conduction and Overall Coefficients

$$q = \frac{T_1 - T_4}{\sum R} = \frac{T_1 - T_4}{\frac{1}{h_i A} + \frac{\Delta X_A}{k_A A} + \frac{1}{h_0 A}} = UA\Delta T_{overall}$$

$$U_i = \frac{1}{A_i \sum R}$$



- Conduction with Internal Heat Generation

Plane wall

$$T = -\frac{\dot{q}}{2k}x^2 + T_0$$

$$T_0 = \frac{\dot{q}}{2k}L^2 + T_w$$

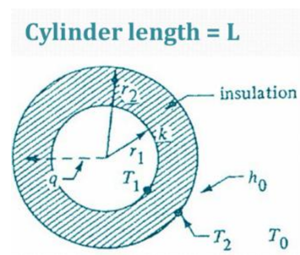
Cylinder

$$T = \frac{\dot{q}}{4k}(R^2 - r^2) + T_w$$

$$T_0 = \frac{\dot{q}}{4k}R^2 + T_w$$

- Critical Thickness of Insulation for a Cylinder

$$q = \frac{2\pi L(T_1 - T_0)}{\frac{ln(r_2/r_1)}{k} + \frac{1}{r_2 h_0}}$$



$$(r_2)_{cr} = \frac{k}{h_0}$$

- if $r_2 < (r_2)_{cr}$, adding more insulation will increase the heat-transfer rate q
- if $r_2 > (r_2)_{cr}$, adding more insulation will decrease the heat-transfer rate q

- *Useful Dimensionless numbers*

$$Re = \frac{\rho\, v\, D}{\mu}$$

$$pr = \frac{\mu/\rho}{k/\rho c_p} = \frac{c_p \mu}{k}$$

$$Nu = \frac{h\, D}{k}$$

- *For laminar Flow*

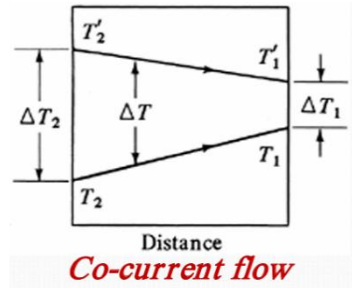
$$Nu = \frac{h_a\, D}{k} = 1.86\,(Re\; Pr\; \frac{D}{L})^{\frac{1}{3}}\, (\frac{\mu_b}{\mu_w})^{0.14}$$

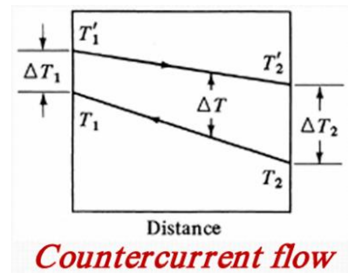
- *For Turbulent Flow*

$$Nu = \frac{h_L\, D}{k} = 0.027 Re^{0.8} Pr^{\frac{1}{3}}\, (\frac{\mu_b}{\mu_w})^{0.14}$$

- Log Mean Temperature Difference and Varying Temperature Drop

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





- Absorptivity and Black Bodies

  - *For Opaque Bodies* $\rho + \alpha = 1$

  - *For Black Bodies* $\rho=0,\ \alpha=1$

ρ: reflectivity or fraction reflected

α: absorptivity or fraction absorbed

- *Radiation from a Body and Emissivity*

$$q = A\,\varepsilon\,\sigma\,T^4$$

q: heat flow [=] W

A: Surface Area of a body [=] m^2

ε*: Emissivity,* ***and it's 1 for a black body***

σ*: Constant = 5.676 ×*10^{-8}*[=] W/*$m^2.K^4$

T: Temperature of the body [=] K

- The net heat of absorption

$$q = A_1 \varepsilon_1 \sigma T_1{}^4 - A_1 \alpha_{12} \sigma T_2{}^4 = A_1 \sigma (\varepsilon_1 T_1{}^4 - \alpha_{12} T_2{}^4)$$

- A further simplification is usually made for engineering purposes, by using one emissivity of the small body at temperature T_2, ε

$$q = A_1 \varepsilon \, \sigma (T_1{}^4 - T_2{}^4)$$

- **Thermal Conductivities of Some Materials at 101.325 kPa (1 atm) Pressure (k in W/m. K)**

TABLE 4.1-1. *Thermal Conductivities of Some Materials at 101.325 kPa (1 Atm) Pressure (k in W/m · K)*

Substance	*Temp. (K)*	*k*	*Ref.*	*Substance*	*Temp. (K)*	*k*	*Ref.*
Gases				Solids			
Air	273	0.0242	(K2)	Ice	273	2.25	(C1)
	373	0.0316		Fire claybrick	473	1.00	(P1)
H_2	273	0.167	(K2)	Paper	—	0.130	(M1)
n-Butane	273	0.0135	(P2)	Hard rubber	273	0.151	(M1)
Liquids				Cork board	303	0.043	(M1)
Water	273	0.569	(P1)	Asbestos	311	0.168	(M1)
	366	0.680		Rock wool	266	0.029	(K1)
Benzene	303	0.159	(P1)	Steel	291	45.3	(P1)
	333	0.151			373	45	
Biological materials and foods				Copper	273	388	(P1)
					373	377	
Olive oil	293	0.168	(P1)	Aluminum	273	202	(P1)
	373	0.164					
Lean beef	263	1.35	(C1)				
Skim milk	275	0.538	(C1)				
Applesauce	296	0.692	(C1)				
Salmon	277	0.502	(C1)				
	248	1.30					

- **Convective-Heat-Transfer Coefficient**

TABLE 4.1-2. *Approximate Magnitude of Some Heat-Transfer Coefficients*

Mechanism	*Range of Values of h*	
	$btu/h \cdot ft^2 \cdot °F$	$W/m^2 \cdot K$
Condensing steam	1000–5000	5700–28 000
Condensing organics	200–500	1100–2800
Boiling liquids	300–5000	1700–28 000
Moving water	50–3000	280–17 000
Moving hydrocarbons	10–300	55–1700
Still air	0.5–4	2.8–23
Moving air	2–10	11.3–55

- **Heat Transfer Properties of Liquid Water, SI Units**

A.2-11 Heat-Transfer Properties of Liquid Water, SI Units

T (°C)	T (K)	ρ (kg/m^3)	c_p ($kJ/kg \cdot K$)	$\mu \times 10^3$ ($Pa \cdot s$, or $kg/m \cdot s$)	k ($W/m \cdot K$)	N_{Pr}	$\beta \times 10^4$ ($1/K$)	$(g\beta\rho^2/\mu^2) \times 10^{-8}$ ($1/K \cdot m^3$)
0	273.2	999.6	4.229	1.786	0.5694	13.3	−0.630	
15.6	288.8	998.0	4.187	1.131	0.5884	8.07	1.44	10.93
26.7	299.9	996.4	4.183	0.860	0.6109	5.89	2.34	30.70
37.8	311.0	994.7	4.183	0.682	0.6283	4.51	3.24	68.0
65.6	338.8	981.9	4.187	0.432	0.6629	2.72	5.04	256.2
93.3	366.5	962.7	4.229	0.3066	0.6802	1.91	6.66	642
121.1	394.3	943.5	4.271	0.2381	0.6836	1.49	8.46	1300
148.9	422.1	917.9	4.312	0.1935	0.6836	1.22	10.08	2231
204.4	477.6	858.6	4.522	0.1384	0.6611	0.950	14.04	5308
260.0	533.2	784.9	4.982	0.1042	0.6040	0.859	19.8	11 030
315.6	588.8	679.2	6.322	0.0862	0.5071	1.07	31.5	19 260

- **Physical Properties of Air at 101.325 kPa (1Atm), SI Units**

A.3-3 Physical Properties of Air at 101.325 kPa (1 Atm Abs), SI Units

T (°C)	T (K)	ρ (kg/m^3)	c_p ($kJ/kg \cdot K$)	$\mu \times 10^5$ ($Pa \cdot s$, or $kg/m \cdot s$)	k ($W/m \cdot K$)	N_{Pr}	$\beta \times 10^3$ ($1/K$)	$g\beta\rho^2/\mu^2$ ($1/K \cdot m^3$)
−17.8	255.4	1.379	1.0048	1.62	0.02250	0.720	3.92	2.79×10^8
0	273.2	1.293	1.0048	1.72	0.02423	0.715	3.65	2.04×10^8
10.0	283.2	1.246	1.0048	1.78	0.02492	0.713	3.53	1.72×10^8
37.8	311.0	1.137	1.0048	1.90	0.02700	0.705	3.22	1.12×10^8
65.6	338.8	1.043	1.0090	2.03	0.02925	0.702	2.95	0.775×10^8
93.3	366.5	0.964	1.0090	2.15	0.03115	0.694	2.74	0.534×10^8
121.1	394.3	0.895	1.0132	2.27	0.03323	0.692	2.54	0.386×10^8
148.9	422.1	0.838	1.0174	2.37	0.03531	0.689	2.38	0.289×10^8
176.7	449.9	0.785	1.0216	2.50	0.03721	0.687	2.21	0.214×10^8
204.4	477.6	0.740	1.0258	2.60	0.03894	0.686	2.09	0.168×10^8
232.2	505.4	0.700	1.0300	2.71	0.04084	0.684	1.98	0.130×10^8
260.0	533.2	0.662	1.0341	2.80	0.04258	0.680	1.87	0.104×10^8

- **Dimensions of Standard Steel Pipe**

A.5-1 Dimensions of Standard Steel Pipe

Nominal Pipe Size (in.)	Outside Diameter		Schedule Number	Wall Thickness		Inside Diameter		Inside Cross-Sectional Area	
	in.	mm		in.	mm	in.	mm	ft^2	$m^2 \times 10^4$
$\frac{1}{8}$	0.405	10.29	40	0.068	1.73	0.269	6.83	0.00040	0.3664
			80	0.095	2.41	0.215	5.46	0.00025	0.2341
$\frac{1}{4}$	0.540	13.72	40	0.088	2.24	0.364	9.25	0.00072	0.6720
			80	0.119	3.02	0.302	7.67	0.00050	0.4620
$\frac{3}{8}$	0.675	17.15	40	0.091	2.31	0.493	12.52	0.00133	1.231
			80	0.126	3.20	0.423	10.74	0.00098	0.9059
$\frac{1}{2}$	0.840	21.34	40	0.109	2.77	0.622	15.80	0.00211	1.961
			80	0.147	3.73	0.546	13.87	0.00163	1.511
$\frac{3}{4}$	1.050	26.67	40	0.113	2.87	0.824	20.93	0.00371	3.441
			80	0.154	3.91	0.742	18.85	0.00300	2.791
1	1.315	33.40	40	0.133	3.38	1.049	26.64	0.00600	5.574
			80	0.179	4.45	0.957	24.31	0.00499	4.641
$1\frac{1}{4}$	1.660	42.16	40	0.140	3.56	1.380	35.05	0.01040	9.648
			80	0.191	4.85	1.278	32.46	0.00891	8.275
$1\frac{1}{2}$	1.900	48.26	40	0.145	3.68	1.610	40.89	0.01414	13.13
			80	0.200	5.08	1.500	38.10	0.01225	11.40
2	2.375	60.33	40	0.154	3.91	2.067	52.50	0.02330	21.65
			80	0.218	5.54	1.939	49.25	0.02050	19.05

- **Different Emissivities**

TABLE 4.10-1. *Total Emissivity, ε, of Various Surfaces*

Surface	*T(K)*	*T(°F)*	*Emissivity, ε*
Polished aluminum	500	440	0.039
	850	1070	0.057
Polished iron	450	350	0.052
Oxidized iron	373	212	0.74
Polished copper	353	176	0.018
Asbestos board	296	74	0.96
Oil paints, all colors	373	212	0.92–0.96
Water	273	32	0.95