BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE, PILANI, PILANI CAMPUS
DEPARTMENT OF CHEMICAL ENGINEERING
Second Semester 2022-2023
CHE F241 Heat Transfer

Mid Sem Test (Closed Book) **Date: 14.03.2023**
Duration: 90 Mins **Marks: 90**

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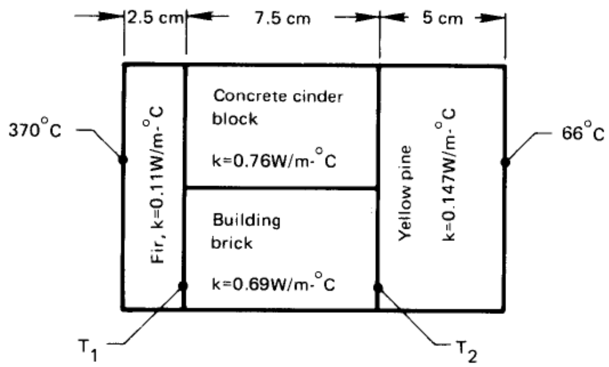
Note: Make suitable assumptions, if necessary.

1. **(15 Marks)**
Consider the composite wall shown in Figure. The concrete cinder block and building brick sections are of equal thickness. Determine T_1, T_2, q and the percentage of q that flows through the brick. Assume one-dimensional heat flow.



2. **(15 Marks)**
A type 316 stainless steel pipe (k = 15 W/m K) has a 6 cm inside diameter and an 8 cm outside diameter with a 2 mm layer of 85% magnesia insulation (k = 0.07 W/m K) around it. Liquid at 112 ^{o}C flows inside. The air around the pipe is at 20 ^{o}C. Calculate the heat transfer per meter length of pipe and overall heat transfer coefficient based on the inside area. The inside and outside heat transfer coefficients are 346 and 6 W/m^2 K, respectively.

3. **(15 Marks)**
Two hundred circumferential fins of rectangular profile are constructed of aluminium and placed on a 6 cm diameter tube maintained at 120 ^{o}C. The length of the fin is 3 cm and its thickness is 2 mm. The fin is exposed to a convection environment at 20 ^{o}C with h = 220 W/m^2 ^{o}C. Calculate the total heat lost from the finned-tube arrangement over the 1 m length. Thermal conductivity of aluminium is 200 W/m ˚C.

4. **(15 Marks)**
A 250^{o}C cylindrical copper billet, 4 cm in diameter and 8 cm long, is suddenly cooled in air at 25^{o}C. The heat transfer coefficient is 5 W/m^2 K. Can this be treated as lumped-capacity cooling? What is the temperature of the billet after 10 minutes.
k = 386 W/m °C; α = 11.23 x 10^{-5} m^2/s; ρ = 8954 kg/m^3; c_p = 0.384 kJ/kg °C

5. **(15 Marks)**
Air at 20 ^{o}C and moving at 15 m/s is warmed by an isothermal steam-heated plate at 110 ^{o}C, 0.5 m in length and 0.5 m in width. Find the average heat transfer coefficient and the total heat transferred. Also, calculate the local heat transfer coefficient, thermal boundary layer thickness, and hydrodynamic boundary layer thickness at the trailing edge ($x = L$).

6. **(15 Marks)**
Air at 300 K and 1 atm enters in a tube bank consists of a square arry of 64 tubes arranged in an in-line position. The tube diameter is 2.5 cm and centre to centre tube spacing is 5.0 cm. The incoming velocity is 10 m/s and the tube wall temperatures are constant at 350 K. Calculate the heat loss by the tubes.

Figure 2-12 | Efficiencies of circumferential fins of rectangular profile, according to Reference 3.

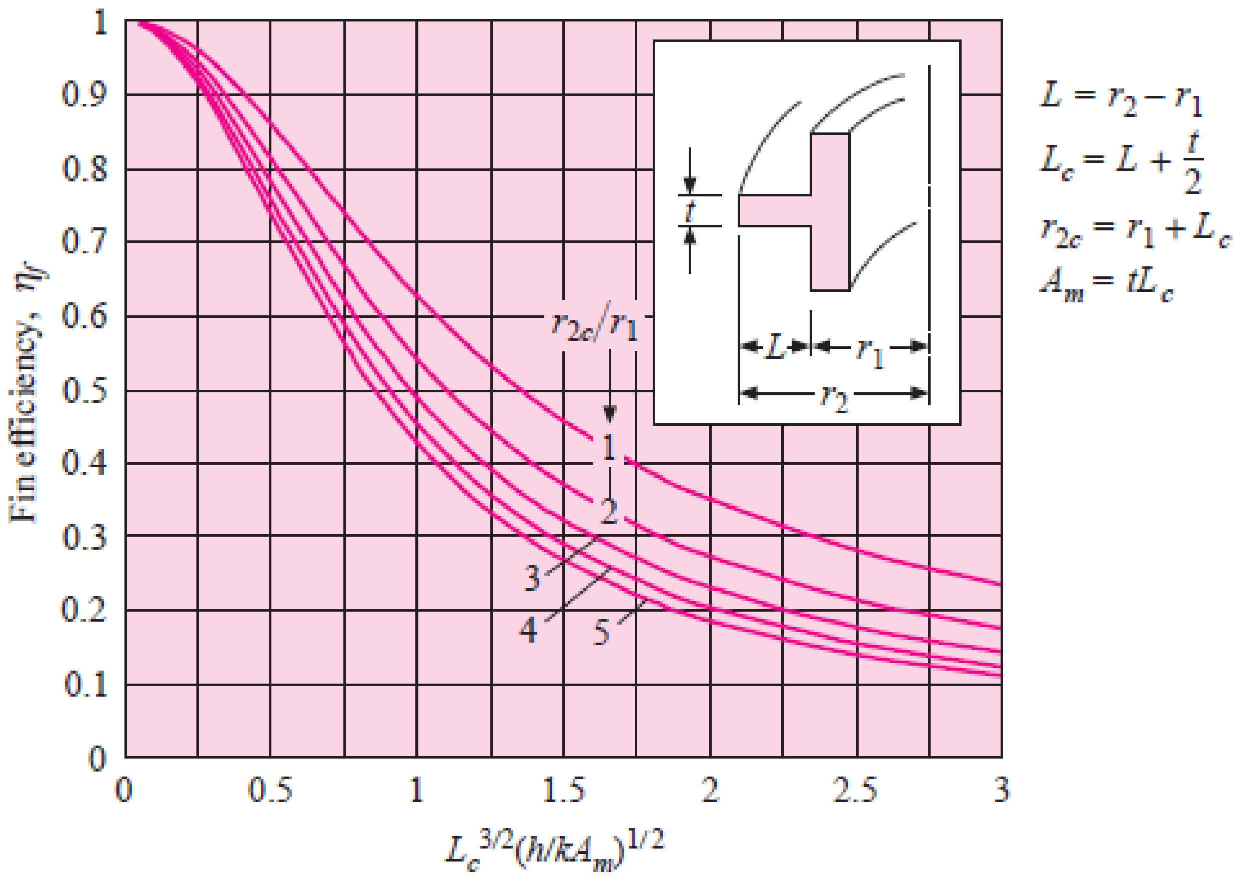


Table A-5 | Properties of air at atmospheric pressure.†

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

Table 5-2 | Summary of equations for flow over flat plates. Properties evaluated at $T_f = (T_w + T_\infty)/2$ unless otherwise noted.

Flow regime	Restrictions	Equation	Equation numl
		Heat transfer	
Laminar, local	$T_w = \text{const}$, $\text{Re}_x < 5 \times 10^5$, $0.6 < \text{Pr} < 50$	$\text{Nu}_x = 0.332\ \text{Pr}^{1/3}\text{Re}_x^{1/2}$	(5-44)
Laminar, local	$T_w = \text{const}$, $\text{Re}_x < 5 \times 10^5$, $\text{Re}_x\ \text{Pr} > 100$	$\text{Nu}_x = \dfrac{0.3387\ \text{Re}_x^{1/2}\ \text{Pr}^{1/3}}{\left[1 + \left(\dfrac{0.0468}{\text{Pr}}\right)^{2/3}\right]^{1/4}}$	(5-51)
Laminar, local	$q_w = \text{const}$, $\text{Re}_x < 5 \times 10^5$, $0.6 < \text{Pr} < 50$	$\text{Nu}_x = 0.453\ \text{Re}_x^{1/2}\ \text{Pr}^{1/3}$	(5-48)
Laminar, local	$q_w = \text{const}$, $\text{Re}_x < 5 \times 10^5$	$\text{Nu}_x = \dfrac{0.4637\ \text{Re}_x^{1/2}\ \text{Pr}^{1/3}}{\left[1 + \left(\dfrac{0.0207}{\text{Pr}}\right)^{2/3}\right]^{1/4}}$	(5-51)
Laminar, average	$\text{Re}_L < 5 \times 10^5$, $T_w = \text{const}$	$\overline{\text{Nu}}_L = 2\ \text{Nu}_{x=L} = 0.664\ \text{Re}_L^{1/2}\ \text{Pr}^{1/3}$	(5-46)
Laminar, local	$T_w = \text{const}$, $\text{Re}_x < 5 \times 10^5$, $\text{Pr} \ll 1$ (liquid metals)	$\text{Nu}_x = 0.564(\text{Re}_x\ \text{Pr})^{1/2}$	
Laminar, local	$T_w = \text{const}$, starting at $x = x_0$, $\text{Re}_x < 5 \times 10^5$, $0.6 < \text{Pr} < 50$	$\text{Nu}_x = 0.332\ \text{Pr}^{1/3}\ \text{Re}_x^{1/2}\left[1 - \left(\frac{x_0}{x}\right)^{3/4}\right]^{-1/3}$	(5-43)
Turbulent, local	$T_w = \text{const}$, $5 \times 10^5 < \text{Re}_x < 10^7$	$\text{St}_x\ \text{Pr}^{2/3} = 0.0296\ \text{Re}_x^{-0.2}$	(5-81)
Turbulent, local	$T_w = \text{const}$, $10^7 < \text{Re}_x < 10^9$	$\text{St}_x\ \text{Pr}^{2/3} = 0.185(\log \text{Re}_x)^{-2.584}$	(5-82)
Turbulent, local	$q_w = \text{const}$, $5 \times 10^5 < \text{Re}_x < 10^7$	$\text{Nu}_x = 1.04\ \text{Nu}_{x\,T_w=\text{const}}$	(5-87)
Laminar-turbulent, average	$T_w = \text{const}$, $\text{Re}_x < 10^7$, $\text{Re}_{\text{crit}} = 5 \times 10^5$	$\overline{\text{St}}\ \text{Pr}^{2/3} = 0.037\ \text{Re}_L^{-0.2} - 871\ \text{Re}_L^{-1}$	(5-84)
		$\overline{\text{Nu}}_L = \text{Pr}^{1/3}(0.037\ \text{Re}_L^{0.8} - 871)$	(5-85)
Laminar-turbulent, average	$T_w = \text{const}$, $\text{Re}_x < 10^7$, liquids, μ at T_∞, μ_w at T_w	$\overline{\text{Nu}}_L = 0.036\ \text{Pr}^{0.43}(\text{Re}_L^{0.8} - 9200)\left(\frac{\mu_\infty}{\mu_w}\right)^{1/4}$	(5-86)
		Boundary-layer thickness	
Laminar	$\text{Re}_x < 5 \times 10^5$	$\frac{\delta}{x} = 5.0\ \text{Re}_x^{-1/2}$; $\frac{\delta_t}{\delta} = \frac{1}{1.026}\text{Pr}^{-1/3}\left[1 - \left(\frac{x_0}{x}\right)^{3/4}\right]^{1/3}$	
Turbulent	$\text{Re}_x < 10^7$, $\delta = 0$ at $x = 0$	$\frac{\delta}{x} = 0.381\ \text{Re}_x^{-1/5}$	
Turbulent	$5 \times 10^5 < \text{Re}_x < 10^7$, $\text{Re}_{\text{crit}} = 5 \times 10^5$, $\delta = \delta_{\text{lam}}$ at Re_{crit}	$\frac{\delta}{x} = 0.381\ \text{Re}_x^{-1/5} - 10{,}256\ \text{Re}_x^{-1}$	
		Friction coefficients	
Laminar, local	$\text{Re}_x < 5 \times 10^5$	$C_{fx} = 0.332\ \text{Re}_x^{-1/2}$	
Turbulent, local	$5 \times 10^5 < \text{Re}_x < 10^7$	$C_{fx} = 0.0592\ \text{Re}_x^{-1/5}$	
Turbulent, local	$10^7 < \text{Re}_x < 10^9$	$C_{fx} = 0.37(\log \text{Re}_x)^{-2.584}$	
Turbulent, average	$\text{Re}_{\text{crit}} < \text{Re}_x < 10^9$	$\overline{C}_f = \frac{0.455}{(\log \text{Re}_L)^{2.584}} - \frac{A}{\text{Re}_L}$; A from Table 5-1	

Table 6-8 | Summary of forced-convection relations. (See text for property evaluation.)

Subscripts: b = bulk temperature, f = film temperature, ∞ = free stream temperature, w = wall temperature

Geometry	Equation	Restrictions	Equation number
Tube flow	$\mathrm{Nu}_d = 0.023\,\mathrm{Re}_d^{0.8}\mathrm{Pr}^n$	Fully developed turbulent flow, $n = 0.4$ for heating, $n = 0.3$ for cooling, $0.6 < \mathrm{Pr} < 100$, $2500 < \mathrm{Re}_d < 1.25 \times 10^5$	(6-4a)
Tube flow	$\mathrm{Nu}_d = 0.0214(\mathrm{Re}_d^{0.8} - 100)\mathrm{Pr}^{0.4}$	$0.5 < \mathrm{Pr} < 1.5$, $10^4 < \mathrm{Re}_d < 5 \times 10^6$	(6-4b)
	$\mathrm{Nu}_d = 0.012(\mathrm{Re}_d^{0.87} - 280)\mathrm{Pr}^{0.4}$	$1.5 < \mathrm{Pr} < 500$, $3000 < \mathrm{Re}_d < 10^6$	(6-4c)
Tube flow	$\mathrm{Nu}_d = 0.027\,\mathrm{Re}_d^{0.8}\mathrm{Pr}^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$	Fully developed turbulent flow	(6-5)
Tube flow, entrance region	$\mathrm{Nu}_d = 0.036\,\mathrm{Re}_d^{0.8}\mathrm{Pr}^{1/3}\left(\frac{d}{L}\right)^{0.055}$ See also Figures 6-5 and 6-6	Turbulent flow $10 < \frac{L}{d} < 400$	(6-6)
Tube flow	Petukov relation	Fully developed turbulent flow, $0.5 < \mathrm{Pr} < 2000$, $10^4 < \mathrm{Re}_d < 5 \times 10^6$, $0 < \frac{\mu_b}{\mu_w} < 40$	(6-7)
Tube flow	$\mathrm{Nu}_d = 3.66 + \frac{0.0668(d/L)\,\mathrm{Re}_d\mathrm{Pr}}{1 + 0.04[(d/L)\,\mathrm{Re}_d\mathrm{Pr}]^{2/3}}$	Laminar, T_w = const.	(6-9)
Tube flow	$\mathrm{Nu}_d = 1.86(\mathrm{Re}_d\mathrm{Pr})^{1/3}\left(\frac{d}{L}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$	Fully developed laminar flow, T_w = const. $\mathrm{Re}_d\mathrm{Pr}\frac{d}{L} > 10$	(6-10)
Rough tubes	$\mathrm{St}_b\mathrm{Pr}_f^{2/3} = \frac{f}{8}$ or Equation (6-7)	Fully developed turbulent flow	(6-12)
Noncircular ducts	Reynolds number evaluated on basis of hydraulic diameter $D_H = \frac{4A}{P}$ A = flow cross-section area, P = wetted perimeter	Same as particular equation for tube flow	(6-14)
Flow across cylinders	$\mathrm{Nu}_f = C\,\mathrm{Re}_{df}^n\,\mathrm{Pr}^{1/3}$ C and n from Table 6-2	$0.4 < \mathrm{Re}_{df} < 400{,}000$	(6-17)
Flow across cylinders	$\mathrm{Nu}_{df} = 0.3 + \frac{0.62\,\mathrm{Re}_f^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1 + \left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{1/4}}\left[1 + \left(\frac{\mathrm{Re}_f}{282{,}000}\right)^{5/8}\right]^{4/5}$	$10^2 < \mathrm{Re}_f < 10^7$, $\mathrm{Pe} > 0.2$	(6-21)
Flow across cylinders		See text	(6-18) to (6-20) (6-22) to (6-24)
Flow across noncircular cylinders	$\mathrm{Nu} = C\,\mathrm{Re}_{df}^n\,\mathrm{Pr}^{1/3}$ See Table 6-3 for values of C and n.		(6-17)
Flow across spheres	$\mathrm{Nu}_{df} = 0.37\,\mathrm{Re}_{df}^{0.6}$	$\mathrm{Pr} \sim 0.7$ (gases), $17 < \mathrm{Re} < 70{,}000$	(6-25)
	$\mathrm{Nu}_d\mathrm{Pr}^{-0.3}(\mu_w/\mu)^{0.25} = 1.2 + 0.53\,\mathrm{Re}_d^{0.54}$	Water and oils $1 < \mathrm{Re} < 200{,}000$ Properties at T_∞	(6-29)
	$\mathrm{Nu}_d = 2 + \left(0.4\,\mathrm{Re}_d^{1/2} + 0.06\,\mathrm{Re}_d^{2/3}\right)\mathrm{Pr}^{0.4}(\mu_\infty/\mu_w)^{1/4}$	$0.7 < \mathrm{Pr} < 380$, $3.5 < \mathrm{Re}_d < 80{,}000$, Properties at T_∞	(6-30)
Flow across tube banks	$\mathrm{Nu}_f = C\mathrm{Re}_{f,\max}^n\,\mathrm{Pr}_f^{1/3}$ C and n from Table 6-4	See text	(6-17)
Flow across tube banks	$\mathrm{Nu}_d = C\mathrm{Re}_{d,\max}^n\,\mathrm{Pr}^{0.36}\left(\frac{\mathrm{Pr}}{\mathrm{Pr}_w}\right)^{1/4}$	$0.7 < \mathrm{Pr} < 500$, $10 < \mathrm{Re}_{d,\max} < 10^6$	(6-34)
Liquid metals		See text	(6-37) to (6-48)
Friction factor	$\Delta p = f(L/d)\rho u_m^2/2g_c$, $u_m = \dot{m}/\rho A_c$		(6-13)

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
Staggered								
0.6	—	—	—	—	—	—	0.236	0.636
0.9	—	—	—	—	0.495	0.571	0.445	0.581
1.0	—	—	0.552	0.558	—	—	—	—
1.125	—	—	—	—	0.531	0.565	0.575	0.560
1.25	0.575	0.556	0.561	0.554	0.576	0.556	0.579	0.562
1.5	0.501	0.568	0.511	0.562	0.502	0.568	0.542	0.568
2.0	0.448	0.572	0.462	0.568	0.535	0.556	0.498	0.570
3.0	0.344	0.592	0.395	0.580	0.488	0.562	0.467	0.574

Table 6-5 | Ratio of h for N rows deep to that for 10 rows deep, for use with Equation (6-17).

N	1	2	3	4	5	6	7	8	9	10
Ratio for staggered tubes	0.68	0.75	0.83	0.89	0.92	0.95	0.97	0.98	0.99	1.0
Ratio for in-line tubes	0.64	0.80	0.87	0.90	0.92	0.94	0.96	0.98	0.99	1.0

$$u_{max} = u_\infty [S_n/(S_n - d)]$$

$$u_{max} = \frac{u_\infty (S_n/2)}{\left[(S_n/2)^2 + S_p^2\right]^{1/2} - d}$$