





KATHMANDU UNIVERSITY  
End Semester Examination [C]  
June/July 2024

Level : B.E.  
Year : III  
Time : 2 hrs. 30mins.

Course : CHEG 303  
Semester : I  
F. M. : 40

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SECTION "B"  
[5Q × 8 = 40 marks]

Attempt *ALL* questions. Assume suitable data where necessary.

1. A window is made up of two 3 mm glass panes separated by an air layer of thickness 8 mm. The window height is 1.2 m, and the width is 1.0 m. There is air on both sides of the window. On the hot side, the air temperature is +20 °C, and on the cold side the air temperature is -10 °C. The glass material has a thermal conductivity of 1.4 W/(m·K). The convection coefficient for the boundary layer on the hot side is 10 W/(m<sup>2</sup>K), and it is 30 W/(m<sup>2</sup>K) on the cold side. The convection coefficient for the air enclosure between the two glass panes is 5 W/(m<sup>2</sup>K). The system is at steady state. Radiation can be neglected. [2+2+2+2=8]
  - a. What is the heat flux through the window?
  - b. What is the heat rate?
  - c. Calculate all temperatures in the system and make a graph of the temperature profile. (When plotting, assume that each external boundary layer is 1 mm thick.)
  - d. Calculate the heat flux due to pure conduction in the air enclosure between the two panes. Is this flux different from the value found in problem b.? Explain.
  
2. A surface has a reflectivity of 0.15 and a transmissivity of 0. The surface is "grey", hence, its absorptivity can be set equal to its emissivity. The surface temperature is 400 °C, and the surface is completely enclosed in large isothermal surroundings with a temperature of 15 °C. What is the net heat flux from the surface to the surroundings?  
  
Air at 10 °C with a free stream velocity of 10 m/s is flowing in parallel with a long horizontal plate. The plate temperature is controlled and kept constant at 200 °C. The pressure in the system is 1 atm. The local convection heat transfer coefficient can be expressed as  $h = ax^{-0.5}$ , where the  $a = 500 \text{ W/(m}^{1.5}\text{K)}$ , for laminar conditions, and it can be expressed as  $h = bx^{-0.2}$ , where  $b = 2000 \text{ W/(m}^{1.8}\text{K)}$ , for turbulent conditions. Transition from laminar to turbulent conditions is assumed to happen abruptly at a specific position downstream of the leading edge (i.e. the transition zone is assumed to be of zero length). [2+3+3=8]
  - a. Determine the average heat flux in the region from  $x = 0$  to  $x = 0.2 \text{ m}$ .
  - b. Determine the average heat flux in the region from  $x = 0$  to  $x = 5 \text{ m}$ .
  
3. The bottom of a steel (mechanically polished) kettle, which is 200 mm in diameter, is maintained at 114 °C. The pressure is 1 atm. Water is boiling in the pan. At the onset of boiling, the water level is 200 mm. When answering the following questions, the answers should be as accurate as possible. Describe any assumptions made. [3+2+2+1=8]
  - a. What is the power input?
  - b. How long does it take to reach a water level of 100 mm in the kettle?
  - c. What is the ratio of the actual surface heat flux to the critical heat flux?
  - d. Explain what is meant by the Leidenfrost point.

P.T.O.

4. Hot exhaust gas from a combustion process is used in a shell-and-tube heat exchanger to heat 2.5 kg/s of water from 28.7 to 85 °C. The heat exchanger has a single shell and two tube passes. The exhaust gas, which is assumed to have the properties of air, enters the shell at 260 °C and leaves at 93.6 °C. The overall heat transfer coefficient is 180 W/(m<sup>2</sup>K). [5+3=8]
- Use the NTU- $\epsilon$  method and calculate the area of the heat exchanger.
  - Now assume that after some time of operation, a layer of deposits will form inside the tubes, and this extra layer is characterized by a fouling factor of 0.0002 m<sup>2</sup>K/W. Estimate a new overall heat transfer coefficient which includes the fouling effect. Hint: Assume that the heat transfer area is the same inside and outside the tubes, and that the thermal resistance in general can be expressed as  $R'' = 1/U$ .
5. Steam condensing on the outer surface of a thin-walled circular tube of diameter  $D = 50$  mm and length  $L = 6$  m maintains a uniform outer surface temperature of 100 °C. Water flows through the tube at a rate of  $\dot{m} = 0.25$  kg/s, and its inlet and outlet temperatures are  $T_{m,i} = 15$  °C and  $T_{m,o} = 57$  °C. What is the average convection coefficient associated with the water flow?  $c_p$  of water at 36 °C = 4178 J/kg·K.
- Spherical particles with a diameter of 1000  $\mu\text{m}$  are to be heated from 900 to 1200 °C by a hot air stream of constant temperature 1500 °C. The particle density is 3000 kg/m<sup>3</sup>, the specific heat capacity of the particles is 1000 J/(kg·K) and the thermal conductivity of the particles is 10 W/(m·K). The average convection coefficient characterizing the heat transfer between the gas and the particle surface has a value of 300 W/(m<sup>2</sup>K). Assume that the lumped thermal capacitance method can be used, and neglect radiation effects. [4+2+2=8]
- How long does it take to heat a particle as described above?
  - Is the lumped capacitance method valid for this problem? Explain.

Important figures and formulas:

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$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\alpha\nu} \quad q_{\text{rad}} = \varepsilon A_s \sigma (T_s^4 - T_{\text{sur}}^4)$$

$$\overline{Nu}_L = \left\{ 0.825 + \frac{0.387 Ra_L^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}} \right\}^2$$

Laminar flow over an isothermal plate:

$$Nu_x = 0.332 Re_x^{0.5} Pr^{1/3}; Pr > 0.6 \quad Nu_{x,ave} = 2Nu_x \quad \delta = 5x Re_x^{-0.5} \quad \delta = \delta_t Pr^{1/3} = \delta_c Sc^{1/3}$$

Turbulent flow over an isothermal plate:

$$Nu_x = 0.0296 Re_x^{0.8} Pr^{1/3}; [0.6 < Pr < 60] \quad \delta \approx 0.37x Re_x^{-0.2} \quad Re_{x,c} = 500,000$$

Flow with mixed boundary layer conditions over an isothermal plate:

$$Nu_{x,ave} = 0.037 (Re_x^{0.8} - 871) Pr^{1/3}; [0.6 < Pr < 60] \quad [Re_{x,c} < Re_x < 10^8]$$

Laminar flow over a plate with constant heat flux conditions:

$$Nu_x = 0.453 Re_x^{0.5} Pr^{1/3}; Pr > 0.6$$

Turbulent flow over a plate with constant heat flux conditions:

$$Nu_x = 0.0308 Re_x^{0.8} Pr^{1/3}; 0.6 < Pr < 60$$

TABLE 11.4 Heat Exchanger NTU Relations

Flow Arrangement	Relation	
Parallel ow	$NTU = -\frac{\ln[1 - \varepsilon(1 + C_r)]}{1 + C_r}$	(11.28b)
Counterow	$NTU = \frac{1}{C_r - 1} \ln\left(\frac{\varepsilon - 1}{\varepsilon C_r - 1}\right)$	$(C_r < 1)$
	$NTU = \frac{\varepsilon}{1 - \varepsilon}$	$(C_r = 1)$
Shell-and-tube	$(NTU)_1 = -(1 + C_r^2)^{-1/2} \ln\left(\frac{E - 1}{E + 1}\right)$	(11.30b)
	$E = \frac{2\varepsilon_1 - (1 + C_r)}{(1 + C_r^2)^{1/2}}$	(11.30c)
	Use Equations 11.30b and 11.30c with	
$n$ shell passes ( $2n, 4n, \dots$ tube passes)	$\varepsilon_1 = \frac{F - 1}{F - C_r} \quad F = \left(\frac{\varepsilon C_r - 1}{\varepsilon - 1}\right)^{1/n} \quad NTU = n(NTU)_1$	(11.31b, c, d)
Cross-ow (single pass)	$NTU = -\ln\left[1 + \left(\frac{1}{C_r}\right) \ln(1 - \varepsilon C_r)\right]$	(11.33b)
	$NTU = -\left(\frac{1}{C_r}\right) \ln[C_r \ln(1 - \varepsilon) + 1]$	(11.34b)
	$NTU = -\ln(1 - \varepsilon)$	(11.35b)
All exchangers ( $C_r = 0$ )		

$$q_{\text{max}} = C_{\text{min}} (T_{h,i} - T_{c,i}) \quad \varepsilon \equiv \frac{q}{q_{\text{max}}} \quad NTU \equiv \frac{UA}{C_{\text{min}}} \quad C \equiv mc_p \quad C_r \equiv \frac{C_{\text{min}}}{C_{\text{max}}}$$

**TABLE 10.1** Values of  $C_{s,f}$  for various surface-fluid combinations [5-7]

Surface-Fluid Combination	$C_{s,f}$	$n$
Water-copper		
Scored	0.0068	1.0
Polished	0.0128	1.0
Water-stainless steel		
Chemically etched	0.0133	1.0
Mechanically polished	0.0132	1.0
Ground and polished	0.0080	1.0
Water-brass	0.0060	1.0
Water-nickel	0.006	1.0
Water-platinum	0.0130	1.0
<i>n</i> -Pentane-copper		
Polished	0.0154	1.7
Lapped	0.0049	1.7
Benzene-chromium	0.0101	1.7
Ethyl alcohol-chromium	0.0027	1.7

**TABLE A.6** Thermophysical Properties of Saturated Water<sup>a</sup>

Temperature, $T$ (K)	Pressure, $p$ (bars) <sup>b</sup>	Specic Volume (m <sup>3</sup> /kg)		Heat of Vaporization, $h_g$ (kJ/kg)	Specic Heat (kJ/kg · K)		Viscosity (N · s/m <sup>2</sup> )		Thermal Conductivity (W/m · K)		Prandtl Number		Surface Tension, $\sigma \cdot 10^3$ (N/m)	Expansion Coef- ficient, $\beta \cdot 10^4$ (K <sup>-1</sup> )	Temperature, $T$ (K)
		$v \cdot 10^3$	$v_g$		$c_p$	$c_{p,g}$	$\mu \cdot 10^6$	$\mu_g \cdot 10^6$	$k \cdot 10^3$	$k_g \cdot 10^3$	$Pr$	$Pr_g$			
273.15	0.00611	1.000	206.3	2502	4.217	1.854	1750	8.02	569	18.2	12.99	0.815	75.5	-68.05	273.15
275	0.00697	1.000	181.7	2497	4.211	1.855	1652	8.09	574	18.3	12.22	0.817	75.3	-32.74	275
280	0.00990	1.000	130.4	2485	4.198	1.858	1422	8.29	582	18.6	10.26	0.825	74.8	46.04	280
285	0.01387	1.000	99.4	2473	4.189	1.861	1225	8.49	590	18.9	8.81	0.833	74.3	114.1	285
290	0.01917	1.001	69.7	2461	4.184	1.864	1080	8.69	598	19.3	7.56	0.841	73.7	174.0	290
295	0.02617	1.002	51.94	2449	4.181	1.868	959	8.89	606	19.5	6.62	0.849	72.7	227.5	295
300	0.03531	1.003	39.13	2438	4.179	1.872	855	9.09	613	19.6	5.83	0.857	71.7	276.1	300
305	0.04712	1.005	29.74	2426	4.178	1.877	769	9.29	620	20.1	5.20	0.865	70.9	320.6	305
310	0.06221	1.007	22.93	2414	4.178	1.882	695	9.49	628	20.4	4.62	0.873	70.0	361.9	310
315	0.08132	1.009	17.82	2402	4.179	1.888	631	9.69	634	20.7	4.16	0.883	69.2	400.4	315
320	0.1053	1.011	13.98	2390	4.180	1.895	577	9.89	640	21.0	3.77	0.894	68.3	436.7	320
325	0.1351	1.013	11.06	2378	4.182	1.903	528	10.09	645	21.3	3.42	0.901	67.5	471.2	325
330	0.1719	1.016	8.82	2366	4.184	1.911	489	10.29	650	21.7	3.15	0.908	66.6	504.0	330
335	0.2167	1.018	7.09	2354	4.186	1.920	453	10.49	656	22.0	2.88	0.916	65.8	535.5	335
340	0.2713	1.021	5.74	2342	4.188	1.930	420	10.69	660	22.3	2.66	0.925	64.9	566.0	340
345	0.3372	1.024	4.683	2329	4.191	1.941	389	10.89	664	22.6	2.45	0.933	64.1	595.4	345
350	0.4163	1.027	3.846	2317	4.195	1.954	365	11.09	668	23.0	2.29	0.942	63.2	624.2	350
355	0.5100	1.030	3.180	2304	4.199	1.968	343	11.29	671	23.3	2.14	0.951	62.3	652.3	355
360	0.6209	1.034	2.645	2291	4.203	1.983	324	11.49	674	23.7	2.02	0.960	61.4	697.9	360
365	0.7514	1.038	2.212	2278	4.209	1.999	306	11.69	677	24.1	1.91	0.969	60.5	707.1	365
370	0.9040	1.041	1.861	2265	4.214	2.017	289	11.89	679	24.5	1.80	0.978	59.5	728.7	370
373.15	1.0133	1.044	1.679	2257	4.217	2.029	279	12.02	680	24.8	1.76	0.984	58.9	750.1	373.15
375	1.0815	1.045	1.574	2252	4.220	2.036	274	12.09	681	24.9	1.70	0.987	58.6	761	375
380	1.2869	1.049	1.337	2239	4.226	2.057	260	12.29	683	25.4	1.61	0.999	57.6	788	380
385	1.5233	1.053	1.142	2225	4.232	2.080	248	12.49	685	25.8	1.53	1.004	56.6	814	385
390	1.794	1.058	0.980	2212	4.239	2.104	237	12.69	686	26.3	1.47	1.013	55.6	841	390
400	2.455	1.067	0.731	2183	4.256	2.158	217	13.05	688	27.2	1.34	1.033	53.6	896	400
410	3.302	1.077	0.553	2153	4.278	2.221	200	13.42	688	28.2	1.24	1.054	51.5	952	410
420	4.370	1.088	0.425	2123	4.302	2.291	185	13.79	688	29.8	1.16	1.075	49.4	1010	420
430	5.699	1.099	0.331	2091	4.331	2.369	173	14.14	685	30.4	1.09	1.10	47.2		430

Temperature, $T$ (K)	Pressure, $p$ (bars) <sup>a</sup>	Specific Volume (m <sup>3</sup> /kg)		Heat of Vaporization, $h_{fg}$ (kJ/kg)	Specific Heat (kJ/kg·K)		Viscosity (N·s/m <sup>2</sup> )		Thermal Conductivity (W/m·K)		Prandtl Number		Surface Tension, $\sigma \cdot 10^3$ (N/m)	Expansion Coef- ficient, $\beta \cdot 10^6$ (K <sup>-1</sup> )	Temperature, $T$ (K)
		$v \cdot 10^3$	$v_g$		$c_{p,l}$	$c_{p,g}$	$\mu \cdot 10^6$	$\mu_g \cdot 10^6$	$k \cdot 10^3$	$k_g \cdot 10^3$	$Pr$	$Pr_g$			
440	7.333	1.110	0.261	2059	4.36	2.46	162	14.50	682	31.7	1.04	1.12	45.1	—	440
450	9.319	1.123	0.208	2024	4.40	2.56	152	14.85	678	33.1	0.99	1.14	42.9	—	450
460	11.71	1.137	0.167	1989	4.44	2.68	143	15.19	673	34.6	0.95	1.17	40.7	—	460
470	14.55	1.152	0.136	1951	4.48	2.79	136	15.54	667	36.3	0.92	1.20	38.5	—	470
480	17.90	1.167	0.111	1912	4.53	2.94	129	15.88	660	38.1	0.89	1.23	36.2	—	480
490	21.83	1.184	0.0922	1870	4.59	3.10	124	16.23	651	40.1	0.87	1.25	33.9	—	490
500	26.40	1.203	0.0766	1825	4.66	3.27	118	16.59	642	42.3	0.86	1.28	31.6	—	500
510	31.66	1.222	0.0631	1779	4.74	3.47	113	16.95	631	44.7	0.85	1.31	29.3	—	510
520	37.70	1.244	0.0525	1730	4.84	3.70	108	17.33	621	47.5	0.84	1.35	26.9	—	520
530	44.58	1.268	0.0445	1679	4.95	3.96	104	17.72	608	50.6	0.85	1.39	24.5	—	530
540	52.38	1.294	0.0375	1622	5.08	4.27	101	18.1	594	54.0	0.86	1.43	22.1	—	540
550	61.19	1.323	0.0317	1564	5.24	4.64	97	18.6	580	58.3	0.87	1.47	19.7	—	550
560	71.08	1.355	0.0269	1499	5.43	5.09	94	19.1	563	63.7	0.90	1.52	17.3	—	560
570	82.16	1.392	0.0228	1429	5.68	5.67	91	19.7	548	76.7	0.94	1.59	15.0	—	570
580	94.51	1.433	0.0193	1353	6.00	6.40	88	20.4	528	76.7	0.99	1.68	12.8	—	580
590	108.3	1.482	0.0163	1274	6.41	7.35	84	21.5	513	84.1	1.05	1.84	10.5	—	590
600	123.5	1.541	0.0137	1176	7.00	8.75	81	22.7	497	92.9	1.14	2.15	8.4	—	600
610	137.3	1.612	0.0115	1068	7.85	11.1	77	24.1	467	103	1.30	2.60	6.3	—	610
620	159.1	1.705	0.0094	941	9.35	15.4	72	25.9	444	114	1.52	3.46	4.5	—	620
625	169.1	1.778	0.0085	858	10.6	18.3	70	27.0	430	121	1.65	4.20	3.5	—	625
630	179.7	1.856	0.0075	781	12.6	22.1	67	28.0	412	130	2.0	4.8	2.6	—	630
635	190.9	1.935	0.0066	683	16.4	27.6	64	30.0	392	141	2.7	6.0	1.5	—	635
640	202.7	2.075	0.0057	560	26	42	59	32.0	367	155	4.2	9.6	0.8	—	640
645	215.2	2.351	0.0045	361	90	—	54	37.0	331	178	12	26	0.1	—	645
647.3 <sup>a</sup>	221.2	3.170	0.0032	0	∞	∞	45	45.0	238	238	∞	∞	0.0	—	647.3 <sup>a</sup>

TABLE A.4 Thermophysical Properties of Gases at Atmospheric Pressure<sup>a</sup>

$T$ (K)	$\rho$ (kg/m <sup>3</sup> )	$c_p$ (kJ/kg·K)	$\mu \cdot 10^7$ (N·s/m <sup>2</sup> )	$\nu \cdot 10^6$ (m <sup>2</sup> /s)	$k \cdot 10^3$ (W/m·K)	$\alpha \cdot 10^6$ (m <sup>2</sup> /s)	$Pr$
Air, $M = 28.97$ kg/kmol							
100	3.5562	1.032	71.1	2.00	9.34	2.54	0.786
150	2.3364	1.012	103.4	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.720
300	1.1614	1.007	184.6	15.89	26.3	22.5	0.707
350	0.9950	1.009	208.2	20.92	30.0	29.9	0.700
400	0.8711	1.014	230.1	26.41	33.8	38.3	0.690
450	0.7740	1.021	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.030	270.1	38.79	40.7	56.7	0.684
550	0.6329	1.040	288.4	45.57	43.9	66.7	0.683
600	0.5804	1.051	305.8	52.69	46.9	76.9	0.685
650	0.5356	1.063	322.5	60.21	49.7	87.3	0.690
700	0.4975	1.075	338.8	68.10	52.4	98.0	0.695
750	0.4643	1.087	354.6	76.37	54.9	109	0.702
800	0.4354	1.099	369.8	84.93	57.3	120	0.709

Film boiling for a cylinder ( $C = 0.62$ ):

$$\overline{Nu}_D = \frac{\overline{h}_{conv} D}{k_v} = C \left[ \frac{g(\rho_l - \rho_v) h'_{fg} D^3}{\nu_v k_v (T_s - T_{sat})} \right]^{1/4}$$

$$h'_{fg} = h_{fg} + 0.80 c_{p,v} (T_s - T_{sat})$$

$$\overline{h}^{4/3} = \overline{h}_{conv}^{4/3} + \overline{h}_{rad} \overline{h}^{1/3}$$

Critical heat flux ( $C = 0.149$ ):

$$q''_{\max} = Ch_{fg}\rho_v \left[ \frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4}$$

Local minimum heat flux ( $C = 0.09$ ):

$$q''_{\min} = C\rho_v h_{fg} \left[ \frac{g\sigma(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2} \right]^{1/4}$$

Free convection boiling:

$$\overline{Nu}_L = 0.54 Ra_L^{1/4} \quad (10^4 \leq Ra_L \leq 10^7)$$

$$\overline{Nu}_L = 0.15 Ra_L^{1/3} \quad (10^7 \leq Ra_L \leq 10^{11})$$

Nucleate boiling:

$$q''_s = \mu_l h_{fg} \left[ \frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left( \frac{c_{p,l} \Delta T_e}{C_{s,f} h_{fg} Pr_l^n} \right)^3$$

Dynamic vs kinematic viscosity:  $\mu = \rho\nu$

$$t_f = \tau \ln \frac{T_i - T_c}{T_f - T_c} \quad \tau = R_s C_s \quad R_s = \frac{l}{hA_s} \quad C_s = \rho V c \quad Bi = \frac{hL_c}{k} \quad L_c = \frac{V}{A_s}$$