UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE AND ENGINEERING

FINAL EXAMINATION, APRIL 2001

Second Year - Program 6

CHE 212S – HEAT TRANSFER

Examiner - M. Kawaji

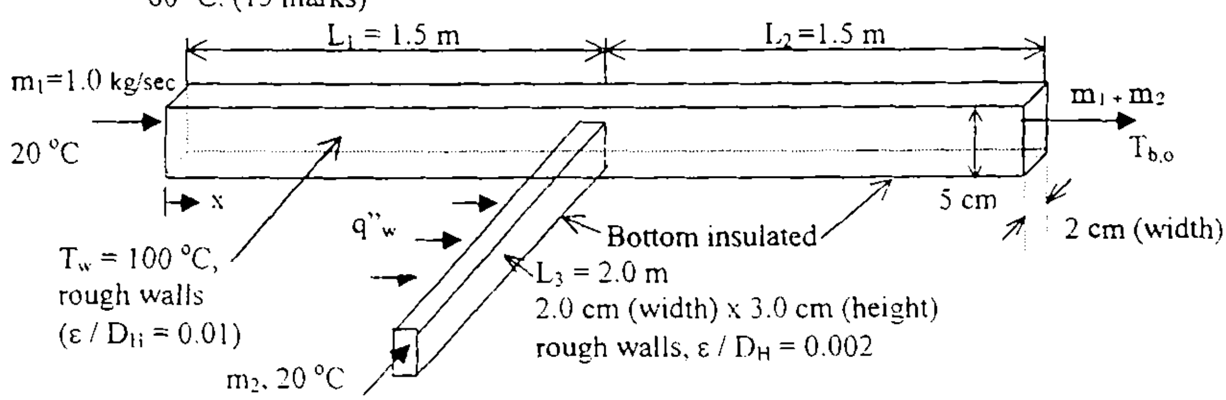
- Lecture notes, a textbook by Kreith (or equivalent) and a calculator of any type are permitted.
- Answer all three questions stating any assumptions you are making in your answer.
- If an iterative solution method is used, show the first step and briefly indicate how subsequent iteration will be performed.
- Tables of water and air properties from Kreith are provided on page 4.

1) Forced Convection (35 Marks)

Consider turbulent convection of water in a heated duct with a 2 cm x 5 cm rectangular cross section and 3.0 m length as shown below. The duct has **rough** inner walls with a relative roughness of ($\varepsilon / D_H = 0.01$). The duct walls are kept at $T_w = 100$ °C everywhere, except for the bottom floor, which is **insulated**. Water enters the duct at 20 °C flowing at a rate of $m_1 = 1.0$ kg/sec. A second stream of water flows through a smaller rectangular duct (2 cm x 3 cm cross section and 2.0 m length) also with **rough** walls ($\varepsilon / D_H = 0.002$) and an **insulated bottom wall**. The second stream joins the main flow in the duct at x = 1.5 m from the main duct entrance.

a) Calculate the bulk temperature of water, $T_{b,o}$ at the outlet of the main duct when there is no flow in the second duct, i.e., $m_2 = 0$. Neglect any entrance effects. (20 marks)

b) The second water stream is now turned on at a certain flow rate, m_2, less than 1.0 kg/s. This stream is heated at a constant wall heat flux of $q_w'' = 50{,}000$ W/m^2, so that the bulk temperature increases from 20 °C to T_{b2} at the junction with the main duct. The mass flow rate in the first half of the main duct (L_1) is still $m_1 = 1.0$ kg/sec, but after mixing with the second stream, the total mass flow rate increases to $m_1 + m_2$. Determine the mass flow rate, m_2, such that the bulk temperature of the mixture would reach $T_{b,o} = 65$ °C at the outlet of the main duct. Hint: For heat transfer rate calculation in the second half (L_2) of the main duct, assume the average bulk temperature of the mixture, $\overline{T_b}$, to be 55 ~ 60 °C. (15 marks)



2) Natural Convection and Radiation Heat Transfer (25 Marks)

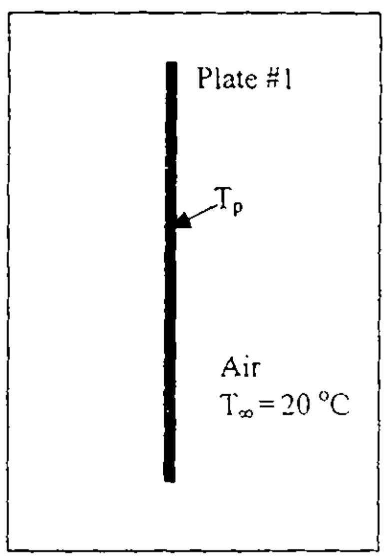
Thick vertical plates (1.0 m wide, 2.0 m high and 10 mm thick) are cooled by natural convection to ambient air at 20 °C as shown below. Both plates are made of steel having a thermal conductivity of k = 50 W/m°C. The first plate generates heat internally at a volumetric heat generation rate of $Q_{gen}''' = 100{,}000$ W/m^3. The second plate does not generate heat internally but receives heat by radiation from a hot radiator ($T_H = 500$ °C) placed 2.0 m away.

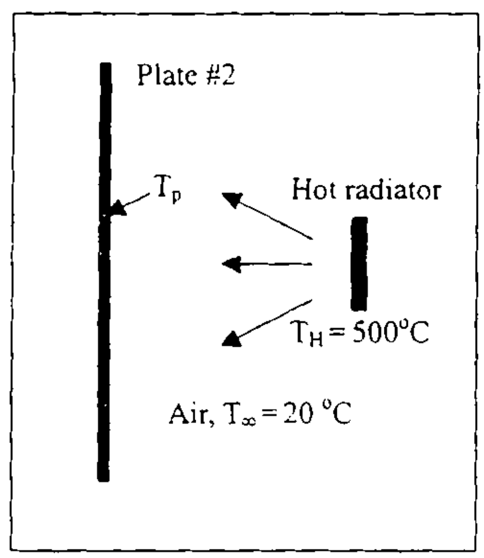
a) Determine the average steady-state temperature of the first plate, T_p, assuming that the temperature is uniform throughout the plate. In reality, the temperature of the first plate would not be uniform. By roughly estimating the temperature variations in the plate, sketch the temperature distributions across the plate thickness and along the height. (15 marks)

b) Calculate the average temperature of the second plate if the plate and the hot radiator surface are both assumed to be black bodies and the rate of radiation heat transfer to the second plate is given by,

$$Q_{rad}\,(W) = \sigma F_{1\text{-}2}\,(T_H^4 - T_p^4)\,A_p$$

where σ is a Stefan-Boltzmann constant (= 5.669×10^{-8} W/m^{2}K^4), $F_{1\text{-}2}$ is a view factor having a value of 0.07, T_p is the average plate temperature, and A_p is the surface area of the plate facing the hot radiator. (10 marks)





3) Heat Exchanger (40 Marks)

A hot stream of oil is to be cooled using cold water in a special cross-flow heat exchanger with both fluids unmixed. The oil flows through 100 finned tubes at a total mass flow rate of $m_o = 5.0$ kg/sec. Cold water enters the heat exchanger at $T_{w,in} = 20$ °C, and flows across the tube bundle at a total mass flow rate of $m_w = 2.5$ kg/sec. The tubes are equipped with fins such that the overall heat transfer coefficient is increased to a value of $U = 1{,}000$ W/m^2 °C. Answer the following questions using the following values of specific heat capacities.

Oil: $C_o = 2{,}100$ J/ kg °C
Water: $C_w = 4{,}200$ J/ kg °C

a) The heat exchanger is operated to obtain equal outlet oil and water temperatures, i.e., $T_{o,ex} = T_{w,ex}$. For this case, draw a temperature diagram for an equivalent double-pipe counterflow heat exchanger, showing all the temperatures at the inlet and outlet. (5 marks)

b) Using both the LMTD and effectiveness-NTU methods, determine the heat transfer area, A_H (m^2), which would provide equal outlet temperatures of oil and water. What is the total heat transfer rate, Q (W)? (15 marks)

c) The oil flow rate is now reduced to 3.0 kg/sec, while the water flow rate and all other parameters remain unchanged. For this new operating condition, determine the total heat transfer rate, Q (W), and the outlet temperatures of both fluids. If you are not sure of the heat transfer area obtained in part (b), use a value of $A_H = 10$ m^2. (10 marks)

d) If the exit temperatures of oil and water are to be made equal again for the reduced oil flow rate, $m_o = 3.0$ kg/sec, either the water flow rate and/or the inlet water temperature, $T_{w,in}$, may be changed. At what new inlet water temperature, $T_{w,in}$, would the two fluids have the same exit temperatures if the water flow rate is to be kept unchanged at 2.5 kg/sec? Comment on the feasibility of this option. (10 marks)

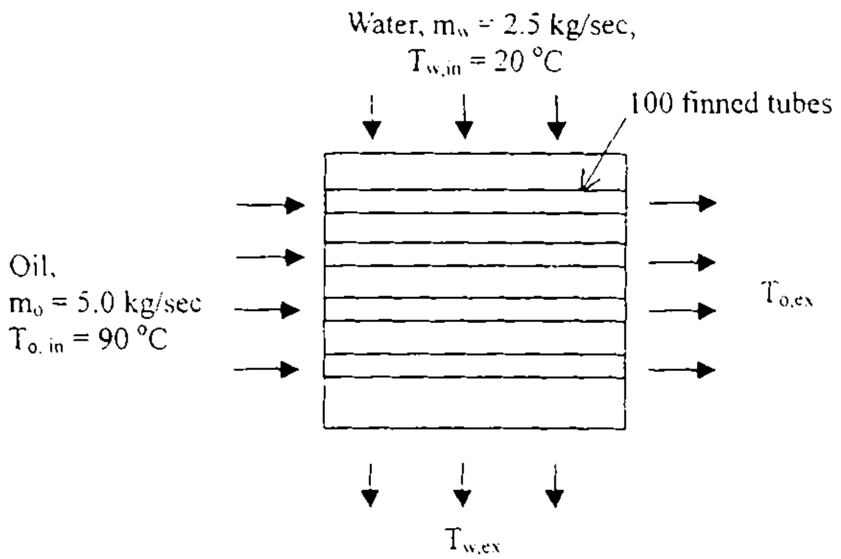


TABLE 13 Water at saturation pressure

Temperature, T °F	K	°C	Density, ρ (kg/m^3) × 6.243 × 10^{-2} = (lb$_m$/ft^3)	Coefficient of Thermal Expansion, $\beta \times 10^4$ (1/K) × 0.5556 = (1/R)	Specific Heat, c_p (J/kg K) × 2.388 × 10^{-4} = (Btu/lb$_m$ °F)	Thermal Conductivity, k (W/m K) × 0.5777 = (Btu/hr ft °F)	Thermal Diffusivity, $\alpha \times 10^6$ (m^2/s) × 3.874 × 10^4 = (ft^2/hr)	Absolute Viscosity, $\mu \times 10^6$ (N s/m^2) × 0.6720 = (lb$_m$/ft s)	Kinematic Viscosity, $\nu \times 10^6$ (m^2/s) × 3.874 × 10^4 = (ft^2/hr)	Prandtl Number, Pr	$\frac{g\beta}{\nu^2} \times 10^{-9}$ (1/K m^3) × 1.573 × 10^{-2} = (1/R ft^3)
32	273	0	999.9	−0.7	4226	0.558	0.131	1794	1.789	13.7	—
41	278	5	1000	—	4206	0.568	0.135	1535	1.535	11.4	—
50	283	10	999.7	0.95	4195	0.577	0.137	1296	1.300	9.5	0.551
59	288	15	999.1	—	4187	0.585	0.141	1136	1.146	8.1	—
68	293	20	998.2	2.1	4182	0.597	0.143	993	1.006	7.0	2.035
77	298	25	997.1	—	4178	0.606	0.146	880.6	0.884	6.1	—
86	303	30	995.7	3.0	4176	0.615	0.149	792.4	0.805	5.4	4.540
95	308	35	994.1	—	4175	0.624	0.150	719.8	0.725	4.8	—
104	313	40	992.2	3.9	4175	0.633	0.151	658.0	0.658	4.3	8.833
113	318	45	990.2	—	4176	0.640	0.155	605.1	0.611	3.9	—
122	323	50	988.1	4.6	4178	0.647	0.157	555.1	0.556	3.55	14.59
167	348	75	974.9	—	4190	0.671	0.164	376.6	0.366	2.23	—
212	373	100	958.4	7.5	4211	0.682	0.169	277.5	0.294	1.75	85.09
248	393	120	943.5	8.5	4232	0.685	0.171	235.4	0.244	1.43	140.0
284	413	140	926.3	9.7	4257	0.684	0.172	201.0	0.212	1.23	211.7
320	433	160	907.6	10.8	4285	0.680	0.173	171.6	0.191	1.10	290.3
356	453	180	886.6	12.1	4396	0.673	0.172	152.0	0.173	1.01	396.5
392	473	200	862.8	13.5	4501	0.665	0.170	139.3	0.160	0.95	517.2
428	493	220	837.0	15.2	4605	0.652	0.167	124.5	0.149	0.90	671.4
464	513	240	809.0	17.2	4731	0.634	0.162	113.8	0.141	0.86	848.5
500	533	260	779.0	20.0	4982	0.613	0.156	104.9	0.135	0.86	1076
536	553	280	750.0	23.8	5234	0.588	0.147	98.07	0.131	0.89	1360
572	573	300	712.5	29.5	5694	0.564	0.132	92.18	0.128	0.98	1766

TABLE 27 Dry air at atmospheric pressure

Temperature, T °F	K	°C	Density, ρ (kg/m^3) × 6.243 × 10^{-2} = (lb$_m$/ft^3)	Coefficient of Thermal Expansion, $\beta \times 10^3$ (1/K) × 0.5556 = (1/R)	Specific Heat, c_p (J/kg K) × 2.388 × 10^{-4} = (Btu/lb$_m$ °F)	Thermal Conductivity, k (W/m K) × 0.5777 = (Btu/hr ft °F)	Thermal Diffusivity, $\alpha \times 10^6$ (m^2/s) × 3.874 × 10^4 = (ft^2/hr)	Absolute Viscosity, $\mu \times 10^6$ (N s/m^2) × 0.6720 = (lb$_m$/ft s)	Kinematic Viscosity, $\nu \times 10^6$ (m^2/s) × 3.874 × 10^4 = (ft^2/hr)	Prandtl Number, Pr	$\frac{g\beta}{\nu^2} \times 10^{-8}$ (1/K m^3) × 1.573 × 10^{-2} = (1/R ft^3)
32	273	0	1.252	3.66	1011	0.0237	19.2	17.456	13.9	0.71	1.85
68	293	20	1.164	3.41	1012	0.0251	22.0	18.240	15.7	0.71	1.36
104	313	40	1.092	3.19	1014	0.0265	24.8	19.123	17.6	0.71	1.01
140	333	60	1.025	3.00	1017	0.0279	27.6	19.907	19.4	0.71	0.782
176	353	80	0.968	2.83	1019	0.0293	30.6	20.790	21.5	0.71	0.600
212	373	100	0.916	2.68	1022	0.0307	33.6	21.673	23.6	0.71	0.472
392	473	200	0.723	2.11	1035	0.0370	49.7	25.693	35.5	0.71	0.164
572	573	300	0.596	1.75	1047	0.0429	68.9	29.322	49.2	0.71	0.0709
752	673	400	0.508	1.49	1059	0.0485	89.4	32.754	64.6	0.72	0.0350
932	773	500	0.442	1.29	1076	0.0540	113.2	35.794	81.0	0.72	0.0193
1832	1273	1000	0.268	0.79	1139	0.0762	240	48.445	181	0.74	0.00236