UNIVERSITY OF RUHUNA

Faculty of Engineering

End-Semester 6 Examination in Engineering: May 2026

Module Number: MN6211 **Module Name: Heat and Mass Transfer (C-23)**

[Three Hours]

[Answer **five (05) questions only**, each question carries **14** marks]

Q1 (a) With the aid of appropriate sketches where necessary, briefly explain the followings.

i) Conduction heat transfer

ii) 1-D steady state heat conduction

iii) Thermal conductivity of a material

iv) Thermal resistance of a plane wall

[4.0 marks]

(b) A 1.0 m high and 1.8 m wide double-pane window consists of two 5.0 mm thick layers of low emissivity glass with a thermal conductivity ($k = 0.85$ W/m·K). They are separated by an 8.0 mm wide stagnant airspace with a thermal conductivity ($k = 0.03$ W/m·K). On a normal day, the room is maintained at 22 °C while the temperature of the outdoors is (– 11 °C). Take the convection heat transfer coefficients which include the effects of radiation on the inner and outer surfaces of the window to be 15 W/m²·K and 35 W/m²·K, respectively.

Clearly stating any assumptions, answer below questions.

i) Draw the thermal resistance network and calculate the total thermal resistance. [3.0 Marks]

ii) Determine the steady rate of heat transfer through the double-pane window. [3.0 Marks]

iii) Find the inner surface temperature of the window.

[2.0 Marks]

iv) If the temperature inside dropped to 19 °C, what is the percentage drop in the rate of heat transfer. [2.0 Marks]

Q2 (a) The maximum use temperature for an ASTM A240 410S stainless steel plate is 649 °C. The plate is treated such that it exhibits the following spectral emissivity:

$$\varepsilon_\lambda = \begin{cases} \varepsilon_1 = 0.8, & 0 \le \lambda < 3.25\ \mu\text{m} \\ \varepsilon_2 = 0.6, & 3.25\ \mu\text{m} \le \lambda < 10.3\ \mu\text{m} \\ \varepsilon_3 = 0.3. & 10.3\ \mu\text{m} \le \lambda < \infty \end{cases}$$

Determine the following,

i. The average emissivity of the surface.

[04 Marks]

ii. The rate of radiation emission from the surface, in W/m^2 at the maximum use temperature.

[04 Marks]

(Refer Table Q2 for Blackbody Radiations Functions)

Table Q2 – Blackbody Radiation Function

λT, $\mu m \cdot K$	f_λ	λT, $\mu m \cdot K$	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

(b) Provide a brief explanation of the following:

i. Blackbody.

ii. Diffusely emitting surface.

iii. Gray surface.

iv. Absorptivity.

[04 Marks]

(c) Explain the variation of the blackbody emissive power with wavelength for different temperatures using the Wien's Displacement Law.

[02 Marks]

Q3 (a) Cold water (c_p = 4180 J/kg·K) enters the tubes of a heat exchanger with two shell passes and 20 tube passes at 15 °C at a rate of 4 kg/s, while hot oil (c_p = 2200 J/kg·K) enters the shell at 130 °C at the same mass flow rate and leaves at 60 °C. If the overall heat transfer coefficient based on the outer surface of the tube is 220 W/m² K. Determine the following using the LMTD method,

i. The rate of heat transfer.

[04 Marks]

ii. The heat transfer surface area on the outer side of the tube.

[04 Marks]

(Refer Figure Q3 for Correction Factor, F)

(b) Explain the different types of fouling encountered during heat exchanger operation.

[04 Marks]

(c) Briefly explain the term, "Fouling Factor" and its importance in heat exchanger design.

[02 Marks]

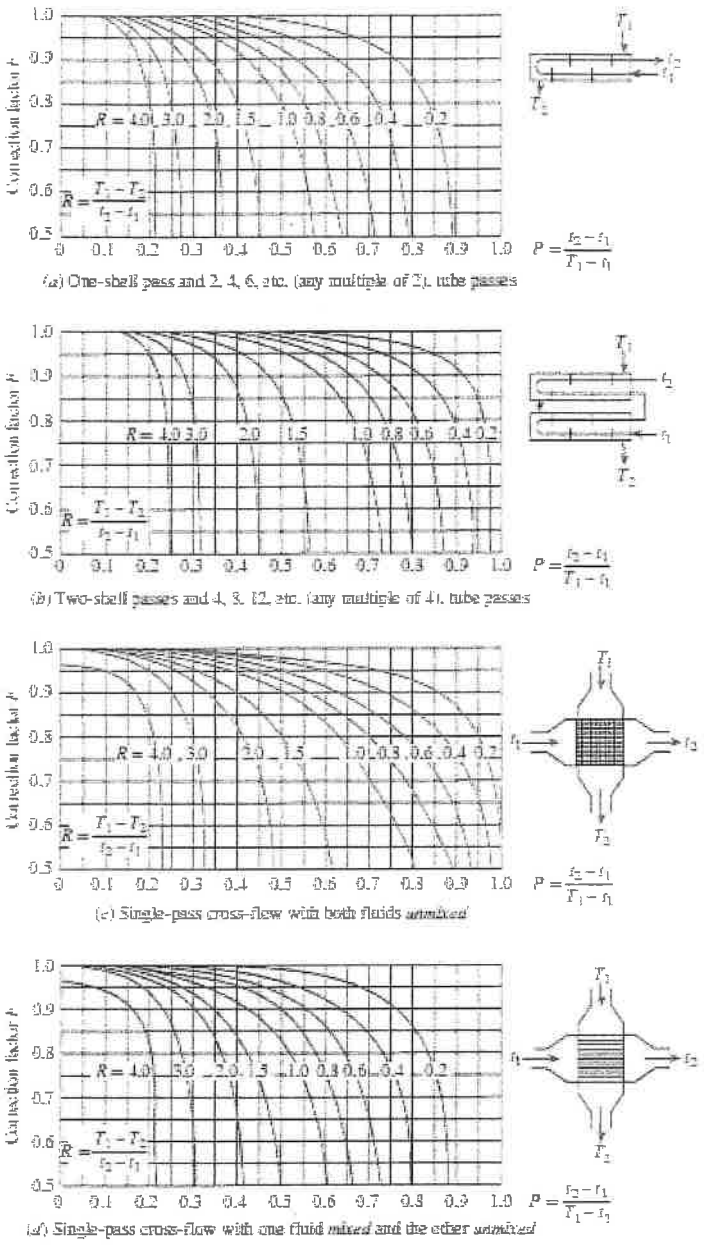


Figure Q3 - Correction factor *F* charts for common shell-and-tube and cross flow heat exchangers.

Q4 (a) Define convective heat transfer and explain the fundamental difference between natural (and forced convection. Illustrate each mode with one relevant everyday application.

[03 Marks]

(b) Explain the variation of the local heat transfer coefficient with respect to velocity boundary layer development on a heated flat plate.

[05 Marks]

(c) Explain **four** strategies to improve convective heat transfer.

[04 Marks]

(d) Discuss the merits of staggered tube arrangements in heat exchangers.

[02 Marks]

Q5 In a ship, feed water entering to the furnace of a boiler is preheated by the jacket water at 90 °C flowing through the heat exchanger tubes of a tube bank. Feed water enters the tube bank at 20 °C and 1 atm with a mean velocity of 3.5 m/s, and flow over the tubes in normal direction. The outer diameter of the tubes is 1.5 cm, and the tubes are arranged in-line with longitudinal and transvers pitches of SL = ST= 6 cm. There are 6 rows in the flow direction with 12 tubes in each row as shown in the Figure Q5. Determine;

i) The exit temperature of the feed water

ii) The rate of heat transfer per unit length of the tubes

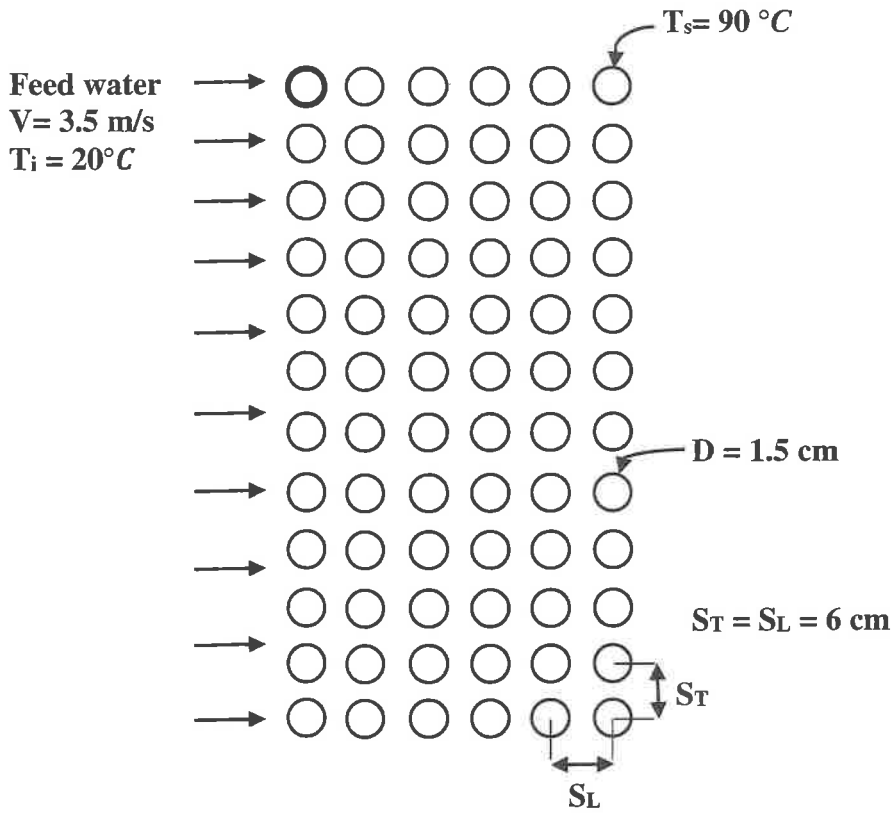


Figure Q5

Table Q5(1) Correction Factor

Correction factor F to be used in $Nu_{D,N_L} = FNu_D$ for $N_L < 16$ and $Re_D > 1000$ (from Zukauskas, Ref 15, 1987).

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

Table Q5(2) Nusselt Number Correlations

Nusselt number correlations for cross flow over tube banks for N > 16 and 0.7 < Pr < 500 (from Zukauskas, Ref. 15, 1987)*

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	$Nu_D = 0.031(S_T/S_L)^{0.2}\ Re_D^{0.8} Pr^{0.36} (Pr/Pr_s)^{0.25}$

Table Q5(3) Properties of water

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	0.416×10^{-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	4205	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	0.0245	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	1.36	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}			

Note:

The exit temperature of the fluid can be determined from

$$T_e = T_s - (T_s - T_i).e^{-\frac{h.A_s}{\dot{m}.C_p}}$$

The total heat transfer rate;

$$q = h.A_S \Delta T_{in}$$

$$A_S = N(\pi DL)$$

$$\Delta T_{in} = \frac{(T_S - T_e) - (T_S - T_i)}{In[(T_S - T_e)/(T_S - T_i)]}$$

All symbols are given their usual notations.

[14 Marks]

Q6 (a) Briefly explain the terms below.

i) Lumped system

ii) Time constant of a lumped system

iii) Characteristic length

iv) Biot number

[6.0 Marks]

(b) A glass 7.0 cm high and 6.0 cm in diameter is used to heat up milk by placing it filled with milk in a large pan filled with hot water at 60 °C. The milk is stirred continuously to maintain a uniform temperature throughout the heating process. If the heat transfer coefficient between the water and the glass is 120 W/m^2.K, answer the questions below by making all necessary assumptions.
(Thermal conductivity, density, and specific heat of of milk at 20 °C; are 0.607 W/m^2.K, 998 kg/m^3, and 4.182 kJ/kg.K, respectively.)

i) Calculate the characteristic length and the Biot number for the glass of milk and comment on the applicability of the "Lumped System Analysis". [4.0 Marks]

ii) Determine the time required for the milk to warm up from 3 °C to 38 °C.

[4.0 Marks]

The temperature of a body T(t) at a time t is given by,

$$\frac{T(t) - T_\infty}{T_i - T_\infty} = e^{-bt}$$

Where,

$$b = \frac{hAs}{\rho VCp}$$

All symbols are given in their usual notation.