Program: BSc. in ME (6th Semester)

Date: 14 May, 2024
Time: 10.00 AM to 1.00 PM

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ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

ORGANIZATION OF ISLAMIC COOPERATION (OIC)

DEPARTMENT OF MECHANICAL AND PRODUCTION ENGINEERING

Semester Final Examination
Course Number: ME 4613
Course Title: Applied Heat Transfer

Summer Semester: 2022-2023
Full Marks: 150
Time: 3 Hours

There are 6 (Six) questions. Answer all of them. Marks of each Question and the corresponding CO and PO are written in the brackets. The symbols have their usual meanings. All the necessary equations are attached afterward. Assume reasonable values for any missing data. Programmable calculators are not allowed. Do not write on this question paper.

1. a) Draw the typical boiling curve for water at 1 atm pressure and identify the different boiling regimes. Also, explain the characteristics of each regime in detail. (10) (CO1) (PO1)

   b) Explain with necessary equations that, for the same inlet and outlet temperature of the hot and cold fluid, counter-flow heat exchangers are smaller in size than parallel-flow heat exchangers. (5) (CO1) (PO1)

2. a) Develop the equations of overall heat transfer coefficient and Log Mean Temperature Difference (LMTD) for counter-flow double pipe heat exchangers. (20) (CO2) (PO2) (P1,P2)

   b) For phase change heat exchangers, derive that, (10) (CO2) (PO2) (P1,P2)

$$T_o = T_i + (T_{sat} - T_i)\left(1 - \exp\left(-\frac{UA}{C}\right)\right)$$

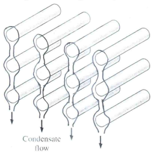
3. a) A heat exchanger is to cool ethylene glycol (C_p = 2560 J/kgK) flowing at a rate of 3.5 kg/s from 80°C to 40°C by water (C_p = 4180 J/kgK) that enters at 20°C flowing at a rate of 2.4 kg/s. The overall heat transfer coefficient based on the inner surface area of the tube is 250 W/m^{2}K. Determine the heat transfer area for (15) (CO3) (PO3) (P1,P2)
   i) counter-flow DPHX
   ii) parallel-flow DPHX
   iii) one shell pass and four tube passes, STHX
   iv) cross-flow, one fluid unmixed, CFHX
   v) cross-flow, both fluids unmixed, CFHX

   b) Hot oil (C_p = 2440 J/kgK) is to be cooled by water in a 2-shell-pass and 8-tube-pass heat exchanger. The tubes are thin-walled and are made of copper with an internal diameter of 1.4 cm. The length of each tube pass in the heat exchanger is 5 m, and the overall heat transfer coefficient is 310 W/m^{2}K. Water (C_p = 4180 J/kgK) flows through the tubes at a rate of 0.2 kg/s, and the oil through the shell at a rate of 0.3 kg/s. The water and the oil enter at temperatures of 20°C and 150°C, respectively. Determine the rate of heat transfer in the heat exchanger and the outlet temperatures of the water and the oil. If the water flow rate is reduced to 0.1 kg/s, what will be the new outlet temperatures? (15) (CO3) (PO3) (P1,P2)

4. Oil is to be heated from 30°C using hot water at 100°C. Oil flow rate is 0.1.kg/s, while water flow rate is 0.5 kg/s. The heat exchanger is made of 2 x 1 1/4 std. type M copper tubing that is 5.0 m long. Using appropriate fouling factors ($R_{d,w}$ = 0.00035 m^2/KW and $R_{d,o}$ = 0.00088 m^2/KW), rate the new and used DPHX, if water flows in the pipe. (25) (CO4) (PO4) (P1,P4)

5. a) Imagine you're the chief engineer of a cutting-edge steam power plant, where every detail counts for optimal performance. In this scenario, the condenser operates under a pressure of 9.593 kPa, and steam condenses on the outer surfaces of pipes as cooling water circulates within. Picture this: the pipes, with an outer diameter of 3 cm, are diligently maintained at a constant surface temperature of 30°C. Now, here's the challenge: you're tasked with determining the rate of heat transfer to the cooling water, but there's a twist. You must consider three different scenarios: (15) (CO4) (PO4) (P1,P4)

i) the orientation of the pipe is horizontal
ii) the orientation of the pipe is vertical
iii) 12 horizontal tubes are arranged in a rectangular array of 3 tubes high and 4 tubes wide



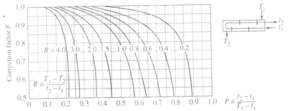
Your mission is to calculate the rate of heat transfer for each scenario and then select either vertical or horizontal orientation which reigns supreme. Choose wisely, for the future of your plant may depend on it.

b) A flow rate of 2.5 kg/s of water, C_p = 4.19 kJ/kgK, enters one end of a counterflow heat exchanger at a temperature of 20°C and leaves at 40°C. Oil (C_p = 1964 J/kgK) enters the other side of the heat exchanger at 50°C and leaves at 30°C. If the heat exchanger were made infinitely large while the entering temperatures and flow rates of water and oil remained constant, what would be the rate of heat transfer in the heat exchanger be? (10) (CO4) (PO4) (P1,P4)

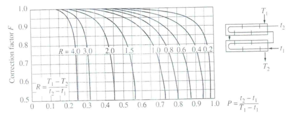
6. a) A cross-flow air-to-water heat exchanger with an area of 52.4 m^2 is used to heat water (C_p = 4180 J/kg k) with hot air (C_p = 1010 J/kgK). Water enters the heat exchanger at 20°C at a rate of 4 kg/s, while air enters at 100°C at a rate of 9 kg/s. If the overall heat transfer coefficient based on the water side is 260 W/m^2K, determine the heat transfer rate and outlet temperatures. Assume one fluid mixed, and the other unmixed. (15) (CO3) (PO3) (P1,P2)

b) Consider a 0.5-m×0.5-m thin square plate in a room at 20°C. One side of the plate is maintained at a temperature of 90°C, while the other side is insulated. Determine the rate of heat transfer from the plate by natural convection if the plate is (a) vertical, (b) horizontal with hot surface facing up, and (c) horizontal with hot surface facing down. (10) (CO3) (PO3) (P1,P2)

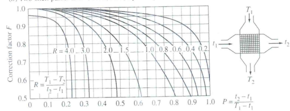
Correction Factor F charts for common heat exchangers:



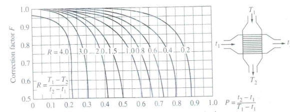
(*a*) One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes



(*b*) Two-shell passes and 4, 8, 12, etc. (any multiple of 4), tube passes



(*c*) Single-pass cross-flow with both fluids *unmixed*



(*d*) Single-pass cross-flow with one fluid *mixed* and the other *unmixed*

Equations for Condensation:

$$h^*_{fg} = h_{fg} + 0.68 C_{pl}(T_{sat} - T_s)$$

$$h_{vert} = 0.943\left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg}k_l^3}{\mu_l(T_{sat} - T_s)L}\right]^{1/4} \quad (\text{W/m}^2\cdot\text{K}), \quad 0 < \text{Re} < 30$$

(for vertical plates or tubes)

$$h_{horiz} = 0.729\left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg}k_l^3}{\mu_l(T_{sat} - T_s)D}\right]^{1/4} \quad (\text{W/m}^2\cdot\text{K})$$

(for horizontally oriented tubes)

$$h_{horiz,\,N\,tubes} = 0.729\left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg}k_l^3}{\mu_l(T_{sat} - T_s)ND}\right]^{1/4} = \frac{1}{N^{1/4}}h_{horiz,\,1\,tube}$$

(for tube banks)

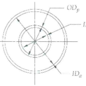
Equations for DPHX:

- Laminar: $Nu = 1.86(Gz)^{1/3}\left(\frac{\mu_b}{\mu_w}\right)^{0.14}$; $\quad Gz = \frac{RePr}{L/D}$
- Turbulent: $Nu = 0.023Re^{0.8}Pr^n$; $\quad n = \begin{cases} 0.4 & : heating \\ 0.3 & : cooling \end{cases}$
- Friction factor, $f = \begin{cases} \xi_{corr}\ [64/Re] & : laminar\ flow \\ (1.82\log_{10}Re - 1.64)^{-2} & : turbulent\ flow \end{cases}$

Pipe area

- Equivalent diameter, $De_p = Dh_p = ID_p$
- Pressure drop, $\Delta P_p = f_p\frac{L}{ID_p}(\frac{1}{2}\rho_p V_p^2)$, $\xi_{corr} = 1$

Annular area

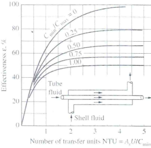


- $Dh_a = ID_a - OD_p$, $\quad De_a = \frac{ID_a^2 - OD_p^2}{OD_p}$
- $\frac{1}{\xi_{corr}} = \frac{1+\kappa^2}{(1-\kappa)^2} + \frac{1+\kappa}{(1-\kappa)\ln(\kappa)}$, $\kappa = OD_p/ID_a$
- $\Delta P_a = (f_a\frac{L}{Dh_a} + 1)(\frac{1}{2}\rho_a V_a^2)$

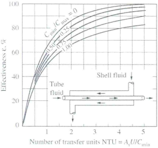
Dimensions and Weights of Types K, L, M and DWV Seamless Copper Tubing:

Nominal or Standard Size, in.	Outside Diameter, in. All Types	Inside Diameter, in.				Wall Thickness, in.				Theoretical Weight Pounds per Linear Foot			
		K	L	M	DWV	K	L	M	DWV	K	L	M	DWV
1/4	0.375	0.305	0.315	*	*	0.035	0.030	*	*	0.145	0.126	*	*
3/8	0.500	0.402	0.430	0.450	*	0.049	0.035	0.025	*	0.269	0.198	0.145	*
1/2	0.625	0.527	0.545	0.569	*	0.049	0.040	0.028	*	0.344	0.285	0.204	*
5/8	0.750	0.652	0.666	*	*	0.049	0.042	*	*	0.418	0.362	*	*
3/4	0.875	0.745	0.785	0.811	*	0.065	0.045	0.032	*	0.641	0.455	0.328	*
1	1.125	0.995	1.025	1.055	*	0.065	0.050	0.035	*	0.839	0.655	0.465	*
1-1/4	1.375	1.245	1.265	1.291	1.295	0.065	0.055	0.042	0.040	1.04	0.884	0.682	0.650
1-1/2	1.625	1.481	1.505	1.527	1.541	0.072	0.060	0.049	0.042	1.36	1.14	0.940	0.809
2	2.125	1.959	1.985	2.009	2.041	0.083	0.070	0.058	0.042	2.06	1.75	1.46	1.07
2-1/2	2.625	2.435	2.465	2.495	*	0.095	0.080	0.065	*	2.93	2.48	2.03	*
3	3.125	2.907	2.945	2.981	3.030	0.109	0.090	0.072	0.045	4.00	3.33	2.68	1.69

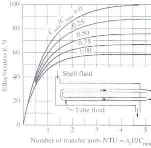
Effectiveness Charts for common heat exchangers:



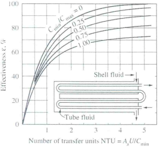
(*a*) Parallel-flow



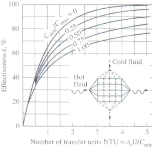
(*b*) Counter-flow



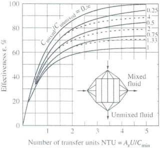
(*c*) One-shell pass and 2, 4, 6, ... tube passes



(*d*) Two-shell passes and 4, 8, 12, ... tube passes



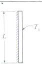
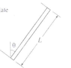
(*e*) Cross-flow with both fluids unmixed



(*f*) Cross-flow with one fluid mixed and the other unmixed

Equations for Natural Convection:

Empirical correlations for the average Nusselt number for natural convection over surfaces

Geometry	Characteristic length L_c	Range of Ra	Nu	
Vertical plate 	L	10^4–10^9	$Nu = 0.59Ra_L^{1/4}$	(9-19)
		10^9–10^{13}	$Nu = 0.1Ra_L^{1/3}$	(9-20)
		Entire range	$Nu = \left\{0.825 + \frac{0.387Ra_L^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right\}^2$ (complex but more accurate)	(9-21)
Inclined plate 	L		Use vertical plate equations for the upper surface of a cold plate and the lower surface of a hot plate Replace g by $g\cos\theta$ for $Ra < 10^9$	
Horiontal plate (Surface area A and perimeter p) (*a*) Upper surface of a hot plate (or lower surface of a cold plate) Hot surface 	A_s/p	10^4–10^7	$Nu = 0.54Ra_L^{1/4}$	(9-22)
		10^7–10^{11}	$Nu = 0.15Ra_L^{1/3}$	(9-23)
(*b*) Lower surface of a hot plate (or upper surface of a cold plate)  Hot surface		10^5–10^{11}	$Nu = 0.27Ra_L^{1/4}$	(9-24)

Property Table

Properties of liquids

Temp. T, °C	Density ρ, kg/m³	Specific Heat c_p, J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m²/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m²/s	Prandtl Number Pr	Volume Expansion Coeff. β, 1/K
				Engine Oil (unused)				
0	899.0	1797	0.1469	9.097×10^{-8}	3.814	4.242×10^{-3}	46,636	0.00070
20	888.1	1881	0.1450	8.680×10^{-8}	0.8374	9.429×10^{-4}	10,863	0.00070
40	876.0	1964	0.1444	8.391×10^{-8}	0.2177	2.485×10^{-4}	2,962	0.00070
60	863.9	2048	0.1404	7.934×10^{-8}	0.07399	8.565×10^{-5}	1,080	0.00070
80	852.0	2132	0.1380	7.599×10^{-8}	0.03232	3.794×10^{-5}	499.3	0.00070
100	840.0	2220	0.1367	7.330×10^{-8}	0.01718	2.046×10^{-5}	279.1	0.00070
120	828.9	2308	0.1347	7.042×10^{-8}	0.01029	1.241×10^{-5}	176.3	0.00070
140	816.8	2395	0.1330	6.798×10^{-8}	0.006558	8.029×10^{-6}	118.1	0.00070
150	810.3	2441	0.1327	6.708×10^{-8}	0.005344	6.595×10^{-6}	98.31	0.00070

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	0.415×10^{-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	4206	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	0.0246	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	1.35	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}			